Review of Biological Reference Points Used in Bering Sea and Aleutian Islands (King and Tanner) Crab Management

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M.S.M. Siddeek

Regional Information Report No. 5J02-06
Alaska Department of Fish & Game
Division of Commercial Fisheries
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ABSTRACT

The overfishing and overfished criteria specified in the 1999 crab fisheries management plan attracted much criticism because they were largely borrowed from groundfish management criteria without any consideration given to the unique life history and fishery characteristics of crab populations. In light of this criticism, this report provides methods to determine the overfishing and overfished reference points using crab-specific growth, mortality, reproduction, and fishery parameters. The harvest rate- and biomass-based limit and target reference points for seven Bering Sea and Aleutian Islands king and Tanner crab stocks were determined by length-based simulations using currently effective legal size limits. The per-recruit analyses were based on constant mortality within respective stages of crabs and normal probability model of molt (growth) increment. These simplified assumptions were needed because the prime objective of this report was to develop crab-specific biological reference points (BRPs) estimation methods for a wide range of crab stocks, especially the data-poor ones. To improve the BRP estimation methods presented in this report, future research could focus on incorporating sex, size, and shell age specific mortality; performing sensitivity analysis of BRPs to varying legal size limits; and determining BRPs based on appropriate levels of spawner escapement.

EXECUTIVE SUMMARY

Following the 1996 amendments of the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA, 1996), the 1989 crab Fishery Management Plan (FMP) was substantially revised by the Crab Plan Team (CPT) in 1999 (NPFMC 1999) and has been used since then. The overfishing and overfished criteria specified in this revision attracted much criticism because they were largely borrowed from groundfish management criteria without any consideration given to the unique life history and fishery characteristics of crab populations. In light of this criticism, this report focuses on developing methods to determine overfishing and overfished criteria with crab-specific growth, mortality, reproduction, and fishery parameters.

This report first reviews some topics relevant for defining overfishing in crab fisheries that were discussed in the 1994 overfishing definition report (Rosenberg et al. 1994), Final Rule guidelines on National Standard 1 published in the Federal Register in 1998, and the technical guidance to implement the revised National Standard 1 guidelines report (Restrepo et al. 1998). In this report, a number of suggestions made by Restrepo et al. (1998) were used as guidelines in formulating the preferred Alternative 2 for Bering Sea and Aleutian Islands (BSAI) crab stocks.

The following two alternatives are considered:

Alternative 1. Status Quo. No revision to the 1999 crab overfishing definition would be made, and the definitions would not be updated in the FMP.

Alternative 2. (Preferred) Redefine some of the overfishing definitions and their analysis methods and update those definitions and analysis methods in the FMP.

The Maximum Sustainable Yield (MSY) definition for BSAI crab stocks under Alternative 1 followed the National Marine Fisheries Service (NMFS) National Standard 1 guidelines and complies with the MSFCMA. Therefore, the definition remains the same under Alternative 2. However, the estimation method requires some modifications.

First, under Alternative 1, the MSY was estimated considering the total of male and female mature crabs. Consequently, this MSY can be compared only with the total harvest of male and female crabs. However, only males are legally harvested in the BSAI crab fisheries. Therefore, for fishery performance determination, MSY should be estimated considering only the legal male portion of the total biomass, or at most, male mature biomass. Second, MSY was estimated assuming MSY fishing mortality (F_{MSY}) = natural mortality (M). However, the simulation results on seven BSAI crab stocks (Bristol Bay red king crab *Paralithodes camtschaticus*, St. Matthew Island blue king crab *P. platypus*, Pribilof Islands blue king crab, Eastern Aleutian Islands golden king crab *Lithodes aequispinus*, and Western Aleutian Islands golden king crab, and Bering Sea Tanner crab *Chionoecetes bairdi* and snow crab *C. opilio*) indicated that F_{MSY} was rarely equal to M and F_{MSY} could take any value—above, equal, or below M—depending on the steepness of underlying stock-recruitment relationships and other vital stock parameters.

Estimate of MSY under Alternative 2

The MSY is equal to the multiplication of the legal male portion of MSY producing total mature biomass, $SSB(F_{MSY})$, and harvest rate, $E(F_{MSY})$. The simulation method described in this report provides the means to estimate $E(F_{MSY})$ and MSY producing total mature biomass over virgin total mature biomass, $SSB(F_{MSY})/SSB(0)$, ratio. The median value of $E(F_{MSY})$ estimates for plausible ranges of stock parameter values is taken as the MSY level harvest rate. The legal male $SSB(F_{MSY})$ in the stock is estimated from the median $SSB(F_{MSY})/SSB(0)$ ratio estimated at the same plausible ranges of stock parameter values, an estimate of virgin population, $SSB(0)$, during a selected period (not necessarily the 1983–1997 period), and the proportion of mature males in the simulated $SSB(F_{MSY})$. The $SSB(0)$ is determined as the mean of the top 20% of biomass estimates during this period.

Although the first sentence of the "MSY Control Rule" in Alternative 1 is in accordance with the National Standard guidelines, the subsequent sentence, interpreting the Rule for BSAI king and Tanner crab stocks, does not cover the full biomass range. Furthermore, the justifications for equating F_{MSY} to M in the Maximum Fishing Mortality Threshold (MFMT) definition as well as in the MSY control rule, and equating MSY stock size to an average size of the total mature biomasses for 1983–1997 are questionable.

Under Alternative 2, the default MSY control rule for poorly investigated stocks is redefined as follows:

It is the harvest strategy, which, if implemented, would be expected to result in a long-term average catch approximating MSY under prevailing environmental conditions. The default MSY control rule in terms of fishing mortality for data-poor and less investigated BSAI crab stocks is given by the following set of formulas:

$$F(SSB) = F_{MSY} \bullet SSB \;/\; \left[c \bullet SSB(F_{MSY})\right] \qquad \text{for all} \qquad SSB \le c \bullet SSB(F_{MSY})$$

$$F(SSB) = F_{MSY} \qquad \text{for all} \qquad SSB > c \bullet SSB(F_{MSY})$$

where c = max (1-M, 0.5), MSST = c • $SSB(F_{MSY})$, $F(SSB)$ = fishing mortality as a function of total mature biomass SSB, and $SSB(F_{MSY})$ = total mature biomass at MSY producing level.

In the BSAI crab stock management and rebuilding plans, c is set at 0.5 (i.e., Minimum Spawning Stock Threshold, MSST = ½$SSB(F_{MSY})$), which may not be precautionary. Although king and Tanner crab M estimates are uncertain, they are likely to be below 0.5. Therefore, the c values for MSST estimation should be 0.7 and 0.6 for the king (M = 0.3) and Tanner (M = 0.4) crab stocks, respectively.

The target control rule is not defined under Alternative 1. So, under Alternative 2, a default target control rule for data-poor and less investigated stock is defined as follows:

It is the harvest strategy, which, if implemented, would be expected to result in a long-term average catch approximating Optimum Yield (OY) under prevailing environmental condition. The default target control rule in terms of fishing mortality for BSAI king and Tanner crabs is given by the following set of formulas:

$$F(SSB) = 0.75F_{MSY} \bullet SSB/[\; c \bullet SSB(F_{MSY})] \qquad \text{for all} \qquad SSB \le c \bullet SSB(F_{MSY})$$

$$F(SSB) = 0.75F_{MSY} \qquad \text{for all} \qquad SSB > c \bullet SSB(F_{MSY})$$

The default target control rule may be modified to use as a rebuilding plan for a severely overfished stock as follows:

$$F(SSB) = 0 \quad \text{for all} \quad SSB \le 0.5\ c \bullet SSB(F_{MSY})$$

$$F(SSB) = 0.75 \times 0.75 F_{MSY} \bullet SSB / \ [c \bullet SSB(F_{MSY})]$$

$$\text{for all} \quad 0.5\ c \bullet SSB(F_{MSY}) < SSB \le c \bullet SSB(F_{MSY})$$

$$F(SSB) = 0.75 \times 0.75 F_{MSY} \quad \text{for all} \quad c \bullet SSB(F_{MSY}) < SSB \le SSB(F_{MSY})$$

$$F(SSB) = 0.75 F_{MSY} \quad \text{for all} \quad SSB > SSB(F_{MSY})$$

In addition, a BRP estimation method for crab stocks, which uses limited biological data, is developed in this report. A spreadsheet-based VBA program was written to implement this method. Overfishing threshold parameters, such as F_{MSY} and the corresponding harvest rate $E(F_{MSY})$, and MSST, can be estimated by this method. Using this method, F_{MSY}, $E(F_{MSY})$, and $SSB(F_{MSY})/SSB(0)$ were determined for seven BSAI crab stocks. The $SSB(F_{MSY})/SSB(0)$ ratio with a knowledge of $SSB(0)$ can be used to estimate MSST. Furthermore, Bristol Bay red king crab data were used to demonstrate how actual MSY, MSY stock size, and MSST can be calculated.

The estimates of F_{MSY}, threshold harvest rate, $E(F_{MSY})$, precautionary target harvest rate for biomass above MSST, $E(0.75F_{MSY})$, and MSY producing total mature biomass as a proportion of virgin total mature biomass, $SSB(F_{MSY})/SSB(0)$, for a plausible set of input parameters are listed below for the seven BSAI crab stocks:

Crab Stock	F_{MSY}	$E(F_{MSY})$	$E(0.75F_{MSY})$	$SSB(F_{MSY})/SSB(0)$
Bristol Bay red king crab	0.56	0.43	0.34	0.54
Bering Sea snow crab	0.46	0.36	0.28	0.63
Bering Sea Tanner crab	0.63	0.46	0.37	0.66
St. Matthew Island blue king crab	0.56	0.43	0.34	0.54
Pribilof Islands blue king crab	0.58	0.44	0.35	0.53
Western Aleutian Islands golden king	0.68	0.43	0.35	0.56
Eastern Aleutian Islands golden king	0.66	0.47	0.38	0.57

Based on a logistic model analysis, Roughgarden and Smith (1996) suggested to maintain biomass above $SSB(F_{MSY})$ (around 75% of $SSB(0)$) to achieve ecological stability. The $SSB(F_{MSY})$ values suggested above are over 50% of $SSB(0)$, and appear to be in the right direction to revive a number of depressed BSAI crab stocks.

INTRODUCTION

The management of living resources in the EEZ waters of the U.S. is based on the MSFCMA, first passed by the U.S. Congress in 1976 and amended several times, with the last substantial amendment made in 1996. The 1996 amendments were concerned with redefining OY and stressing a precautionary approach to managing fisheries (Restrepo et al. 1998, Restrepo and Powers 1999). Eight regional fishery management councils (Councils) were established under MSFCMA to manage EEZ fishery resources. These Councils are entrusted with developing FMPs in accordance with MSFCMA policy guidelines to manage fish stocks or stock complexes in their regions of Federal waters. The NPFMC is responsible for managing fishery resources in the EEZ off Alaska and has been managing the king and Tanner crab fisheries in the EEZ of the BSAI by implementing FMPs since 1984. Following the 1996 amendments of the fisheries act (MSFCMA 1996), the 1989 FMP was substantially revised by the CPT in 1999 (NPFMC 1999) and has been used since.

The overfishing and overfished criteria specified in the revision attracted criticism because they were largely borrowed from groundfish management criteria without any consideration given to the particular life history characteristics of crab populations. This report focuses on defining these two criteria for crab populations in light of this criticism, considers crab-specific biological and fisheries characteristics, and suggests methods to determine the overfishing and overfished criteria (BRP levels) applicable to BSAI crab fisheries. Currently available information on seven BSAI crab stocks was used to determine these two BRP levels and is reported in this review.

PURPOSE OF AND NEED FOR THE REVIEW

When the 1999 report on revised overfishing definitions and updates of BSAI crab FMP was prepared, it was agreed by the CPT to review the BRP estimates on a five-year cycle (i.e., next review is due by 2003) or in the event that environmental conditions signal a regime shift. Therefore, the current review of BRP estimation methods is timely and it can be incorporated as a part of any comprehensive review of the crab FMP that may be undertaken by the CPT in the near future. The 1999 report did not fully utilize the technical guidelines on precautionary management prepared by Restrepo et al. (1998). The current review consulted Restrepo et al. (1998) report extensively to prepare the report.

Alternative 2 in NPFMC (1999) defines the overfishing level by a constant fishing mortality MSY-Control Rule equating F_{MSY} to M. When the current F is greater than M, the stock is considered to be in an "overfishing" status. It defines the "overfished" status by the MSST, which is equal to half of the MSY stock size in most cases. If the current biomass is less than MSST, the stock is considered overfished. The MSY stock size is estimated as the average biomass observed over a 15-year period from 1983 to 1997. These surrogates (M for F_{MSY} and mean annual total mature biomass for MSY stock size, $SSB(F_{MSY})$) are identified for crab management because the BSAI crab stocks are poorly understood and rigorous stock assessment methods for a number of stocks are yet to be developed. Furthermore, assessment of crab fisheries has been complicated by the fact that only males are harvested and that recruitment, in many instances, is largely driven by environmental factors rather than density-dependent responses. During the 1990s, CSA, CLA, and LBA have been developed and applied on a number of BSAI crab stocks to determine historical stock trends, size distributions, and alternative harvest strategies (e.g., Zheng et al. 1995a). Besides critically examining the 1999 overfishing definitions, the present review explores the possibility of using a simplified version of the length-based analysis that can be applied to crab stocks with different levels of stock information for BRP estimation.

OVERVIEW OF ISSUES RELEVANT TO BSAI CRAB OVERFISHING DEFINITION

Guidelines to Implement National Standards of MSFCMA in FMP

Review of Overfishing Definition by Rosenberg et al. (1994)

Prior to passage of the Sustainable Fisheries Act (SFA) in 1996, the National Standard guidelines for FMP preparation to comply with MSFCMA (then Magnuson Fishery Conservation Act) were last revised in 1989 with the publication of the 602 guidelines in the Federal Register for FMPs. These guidelines were developed by a panel of fisheries experts to address National Standard 1 (achieving OY) and National Standard 2 (using the best scientific information available) set out in MSFCMA. The 602 guidelines detailed what was needed in each FMP to define overfishing with respect to these National Standards. By 1993, over 100 definitions within FMP's had been approved by NMFS under the 602 guidelines. NMFS convened a team of fisheries experts in 1993 to review all the approved definitions, address their strengths and shortcomings, and to standardize, as far as possible, the criteria and basis for future evaluations of overfishing definitions. The goal of the review was to develop a scientific consensus as to the appropriateness of the definitions and the criteria used in their evaluation. The team's findings (Rosenberg et al. 1994) that are relevant for the present review are listed below:

a. Overfishing definitions should be measurable, operationally unambiguous, based in sound theory, and biologically sensible.
b. An overfishing definition should set a limiting threshold distinct from a fishing target. A fishery should be maintained near its target. If the threshold is exceeded, strong management action should be taken to rebuild the stock to the MSY producing level.
c. An overfishing definition should, at least, prevent recruitment overfishing, which is defined by this review panel as any stock size or level of fishing that would result in expected recruitment below one-half the maximum recruitment.
d. An overfishing definition can be expressed as a threshold harvest control law, which relates target and threshold fishing mortality rates to stock biomass or abundance.
e. Overfishing definitions and harvest control laws should have at least two components: a maximum fishing mortality rate, and a precautionary biomass level below which the maximum fishing mortality rate is reduced to further protect the stock. An additional protection can be provided by the inclusion of an absolute minimum biomass below which the fishery is closed.
f. Additional information on life history characteristics should be incorporated into overfishing definitions where needed.
g. An analysis of uncertainty is needed to evaluate the status of the stock with respect to overfishing definitions.

Scientific review of the pre-1999 FMP definitions of overfishing for BSAI crab stocks was limited to two BSAI stocks: Bristol Bay red king crab and Bering Sea Tanner crab. The

MFMT definition, $F_{0.1}$, was found neutrally conservative as a threshold. The panel observed that the choice of a handling mortality rate strongly affected the calculation of $F_{0.1}$ and needed further investigation.

Revised National Standard 1 Guidelines by NMFS

The MSFCMA, as amended by the SFA in 1996, necessitated significant revision to the National Standard 1 guidelines. In revising the guidelines, policy guidance was taken from MSFCMA and other applicable law. The technical guidance was taken from the overfishing definition review report by Rosenberg et al. (1994) and the scientific literature. The Final Rule guidelines on National Standard 1 (Section 600.310), which was published in the Federal Register in May 1998, was detailed in the crab overfishing definitions review report (NPFMC 1999). Several points relevant to the current BRP review are summarized below:

<u>National Standard 1</u>

"Conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the OY from each fishery for the United States fishing industry."

(a) Definitions Related to Optimum Yield and Overfishing

> "(i) Optimum Yield: The term "optimum," with respect to the yield from a fishery, means the amount of fish that (a) will provide the greatest overall benefit to the nation, particularly with respect to food production and recreational opportunities, and taking into account the protection of marine ecosystems; (b) that is prescribed as such on the basis of maximum sustainable yield from the fishery, as reduced by any relevant economic, social, or ecological factor; and (c) in the case of an overfished fishery, that provides for rebuilding to a level consistent with producing the maximum sustainable yield in such fishery."
>
> (ii) Overfishing: The terms "overfishing" and "overfished" mean a rate or level of fishing mortality that jeopardizes the capacity of a fishery to produce the MSY on a continuing basis.

In this section, the term "overfished" is used to describe any stock or stock complex whose size is sufficiently small that a change in management practices is required to achieve an appropriate level and rate of rebuilding to the MSY producing level.

<u>MSY: Each FMP should include an estimate of MSY</u>

(a) Definitions Related to MSY

> "(i) MSY: the largest long-term average catch that can be taken from a stock or stock complex under prevailing ecological and environmental conditions.
>
> (ii) MSY Control Rule: A harvest strategy, if implemented, would be expected to result in a long-term average catch approximating MSY.
>
> (iii) MSY stock size: the long-term average size of the stock or stock complex, measured in terms of spawning biomass or other appropriate units, that would be achieved under an MSY control rule in which fishing mortality rate is kept constant."

(b) Some Options Available in Specifying MSY

When data are insufficient to estimate MSY directly, other measures of productive capacity that can serve as reasonable proxies for MSY, and may be used to the extent possible. Examples include various reference points $F_{x\%}$ (e.g. $F_{30–40\%}$ that reduces the long term average level of spawner biomass-per-recruit to 30–40% of the long-term average that would be expected in the absence of fishing). The long-term average stock size obtained by fishing year after year at this $F_{x\%}$ under average recruitment may be a reasonable proxy for the MSY stock size, and the long-term average catch so obtained may be a reasonable proxy for MSY. The M may also be a reasonable proxy for the F_{MSY}. If a reliable estimate of virgin stock size is available, a stock size approximately 40% of this value may be a reasonable proxy for the MSY stock size, and the product of this stock size and M may be a reasonable proxy for MSY.

Status Determination Criteria (SDC)

“Each FMP must specify, to the extent possible, objective and measurable SDC for each stock or stock complex covered by the FMP and provide an analysis of how the SDC were chosen and how they relate to reproductive potential. Status determination criteria must be expressed in a way that enables the Council and the Secretary to monitor the stock or stock complex and determine annually whether overfishing is occurring and whether the stock or stock complex is overfished.

The SDC must specify both of the following:

> (i) A MFMT or reasonable proxy thereof. The MFMT may be expressed either as a single number or as a function of spawning biomass or other measure of productive capacity. The MFMT must not exceed the fishing mortality rate or level associated with the relevant MSY control rule. Exceeding the MFMT for a period of one year or more constitutes overfishing.
>
> (ii) A MSST or reasonable proxy thereof. The MSST should be expressed in terms of spawning biomass or other measure of productive capacity. To the extent possible, the MSST should equal whichever of the following is greater: one-half of the MSY stock size, or the minimum stock size at which rebuilding to the MSY level would be expected to occur within 10 years if the stock or stock complex were exploited at the MFMT. Should the actual stock or stock complex size in a given year fall below MSST, the stock or stock complex is considered overfished.”

Ending Overfishing and Rebuilding Overfished Stocks

(a) Definition:

“A threshold, either MFMT or MSST [or both], is being “approached” whenever it is projected that the threshold will be breached within two years, based on trends in fishing effort, fishery resource size, and other appropriate factors.”

The Secretary will immediately notify a Council and request that remedial action be taken whenever the Secretary determines that: overfishing is occurring; stock or stock complex is overfished; F is approaching MFMT; stock size is approaching MSST, or existing remedial action to reverse those previously identified conditions has not resulted in adequate progress.

Within one-year's time of the Secretary's notification, the Council must take remedial action by preparing an FMP, FMP amendment, or proposed regulations.

"(b) A number of factors enter into the specification of the time period for rebuilding:

(1) The status and biology of the stock or stock complex;
(2) Interactions between the stock or stock complex and other components of the marine ecosystem (also referred to as "other environmental conditions");
(3) The needs of fishing communities;
(4) Recommendation by international organizations in which the United States participates; and
(5) Management measures under an international agreement in which the United States participates."

These factors enter into the specification of the time period for rebuilding as follows:

(i) The lower limit of the specified time period (T_{min}) for rebuilding is determined by the status and biology of the stock or stock complex and its interactions with other components of the marine ecosystem, and is defined as the amount of time that would be required for rebuilding with zero level of F.

(ii) If T_{min} is less than 10 years, then the specified time period for rebuilding may be adjusted upward up to 10 years as necessary, unless management measures under an international agreement in which the U.S. participates dictate otherwise.

(iii) If T_{min} is 10 years or greater, then the specified time period for rebuilding may be adjusted upward, except that no such adjustment can exceed T_{min} plus one mean generation time or equivalent period based on the species life history characteristics.

OY

(a) Some Points Related to Specifications of OY

> "(i) The amount of fish that constitutes the OY should be expressed in terms of weight or numbers. However, OY may be expressed as a formula that converts periodic stock assessment results into target harvest levels; in terms of an annual harvest of fish having a minimum weight, length, or other measurements; or as an amount of fish taken only in certain areas, in certain seasons, with particular gear, or by a specified amount of fishing effort.
>
> (ii) The determination of OY requires a specification of MSY, which may not always be possible or meaningful. The OY must still be based on the best scientific information available."

(b) Precautionary Approach

"Councils should adopt a precautionary approach to specification of OY. A precautionary approach is characterized by three features:

> (i) Target reference points, such as OY, should be set safely below threshold reference points.
>
> (ii) A stock or stock complex that is below the size that would produce MSY should be harvested at a lower *F* than if the stock or stock complex were above the size that would produce MSY.
>
> (iii) Criteria used to set target catch levels should be explicitly risk averse, so that greater uncertainty regarding the status or productive capacity of a stock or stock complex corresponds to greater caution in setting target catch levels."

Technical Guidance to Implement the Revised National Standard 1 Guidelines by Restrepo et al. (1998)

The technical guidance to implement the National Standard 1 guidelines was prepared by a panel of fisheries experts and reported in Restrepo et al. (1998). The primary goal of this panel was to provide the guidance on the use of precautionary approaches to implementing the National Standard 1 of the MSFCMA in accordance with the National Standard Guidelines. The report by this panel focused on providing guidance to managers and scientists for specifying OY and for developing reference points to guide management decisions. In particular, the report provides MSY control rules and target-control rules, which could be used in the absence of more specific analysis. Restrepo et al.(1998) report does not propose a default rebuilding plan; instead, it provides four key elements (an estimate of MSY producing biomass, a rebuilding time period, a rebuilding trajectory, and a transition from rebuilding to more optimal management) that should be considered in any rebuilding plan. Several suggestions relevant for the current review are summarized below:

Control Rules

"A control rule describes a reference fishing mortality rate as a function of stock size, *F(SSB)*. It seeks to identify measures of "good" and "bad" stock condition (by comparing perceived stock status with BRPs) as well as the actions that will make the stock condition change from "bad" to "good." According to National Standard 1 guidelines, the MSY control rule is *F(SSB)*, a continuous function of *SSB*, that maximizes the resulting long-term average yield. The MSY control rule is key to identifying the threshold reference points."

Threshold Reference Points

Two critical components of precautionary management are the specification of threshold and target reference points. Under the constant fishing mortality MSY control rule, the MFMT should equal to F_{MSY} and MSST should equal to whichever of the following is greater: one-half of MSY producing biomass, or the minimum stock size at which rebuilding to the MSY level would be expected to occur within 10 years if the stock or stock complex were exploited at MFMT.

Use of Proxies

Proxies will be needed when MSY-related parameters can't be estimated from available data or when their estimated values are unreliable. Proxies are needed under data–moderate and data-poor situations.

(a) Data-Moderate Cases – Reliable estimates of MSY-related quantities are either unavailable or of limited use due to unique life history traits, poor data contrast, or high recruitment variability, but reliable estimates of current stock size and all critical life history (e.g., growth) and fishery (e.g., selectivity) parameters are available. Control rules typically involves parameters such as $F_{x\%}$.

(b) Data-Poor Cases – Reliable estimates of MSY-related quantities are unavailable, as are reliable estimates of either current stock size or critical life history or fishery parameters. Control rules typically involve parameters such as M.

(c) Some Recommended Threshold Reference Point Proxies by Restrepo et al. (1998):

(i) Recruitment Overfishing (for data-moderate case): $F_{20\%}$–$F_{30\%}$. Fishing mortality that produces a long-term average spawner biomass-per-recruit equivalent to that of 20–30% of the long-term average spawner biomass-per-recruit produced at $F = 0$.

(ii) F_{MSY} (for data-moderate case): $F_{30\%}$–$F_{60\%}$. $F_{30\%}$ for stocks believed to have relatively high resilience, $F_{35\%}$ for stocks with average resilience, $F_{40\%}$ for stocks believed to have low-to-moderate resilience, and F_{50}–$F_{60\%}$ for stocks with very low resilience.

(iii) $SSB(F_{MSY})$ (for data-moderate case): The long-term average mature stock biomass corresponding to the above $F_{x\%}$.

Note: For crab BRP estimation, a distinction was made between mature stock biomass, $SSB(F)$, and true spawning stock biomass, $ESB(F)$. The $ESB(F)$ was used in the S–R relationship, and the biomass-based BRP was estimated in terms of unadjusted (for mating ratio) average mature stock biomass ratio, $SSB(F_{MSY})/SSB(0)$, for convenience in application.

(iv) $SSB(0)$ (for data-moderate case): Mean recruitment multiplied by mature stock biomass-per-recruit at $F = 0$.

(v) MSY (for data-moderate case): The equilibrium yield at the above mentioned proxies for F_{MSY} and $SSB(F_{MSY})$.

(vi) F_{MSY} (for data-poor case): $0.8M$ or $0.75M$

(vii) $SSB(F_{MSY})$ (for data-poor case): The long-term average mature stock biomass corresponding to $F = 0.8M$ or $F = 0.75M$.

(viii) $SSB(0)$ (for data-poor case): Estimate of early CPUE may relate to $SSB(0)$. Non-equilibrium production modeling may provide an inference of initial CPUE.

(ix) MSY (for data-poor case): Historical average catch.

The default MSY control rule would then be defined with F set to above mentioned proxy level in equation (2). The default MSST corresponds to c (= max (1–M, ½)) times the above mentioned proxy MSY producing biomass.

(d) "The target reference points, such as OY, should be set safely below threshold reference points. The target reference point provides a safety margin to ensure that the realized F does not exceed MFMT. The target control rule also facilitates rebuilding of stocks by reducing F proportionately at stock sizes below $(1\text{-}M)SSB(F_{MSY})$. Deterministic simulations indicated that fishing at 75%F_{MSY} would result in long-term mean yields of 94% MSY or higher (i.e., only a slight reduction in MSY) and long-term mean biomass levels between 125% and 131% $SSB(F_{MSY})$.

(e) Rebuilding from Overfished Status

"Rebuilding period is linked to generation time because it highlights the time span in the future during which recruitment will begin to depend primarily upon fish that have yet to be born, as opposed to spawners that already exist. The default rebuilding plan for stocks below MSST should be based on the target control rule with the following extensions:

(i) The T_{max} should be 10 years, unless T_{min} is greater than 10 years, then T_{max} should be equal to T_{min} plus one mean generation time.

(ii) The T_{target} should be as short as possible and lower than T_{max}. T_{target} is suggested to be selected so as not to exceed the midpoint between T_{min} and T_{max}.

(iii) If the stock is well below MSST (e.g., $B \leq 1/2$ MSST), it may be necessary to set the F as close to zero as possible for a number of years.

In order to account for uncertainty in stock dynamics, the rebuilding plan should be designed to posses a 50% or higher chance of achieving $SSB(F_{MSY})$ within T_{target} years, and 90% or higher chance of achieving $SSB(F_{MSY})$ within T_{max} years.

(f) Special Considerations

(i) In a mixed-stock fishery, at a minimum, F should not exceed MFMT for any individual stock in a mixed-stock complex except as provided in § 600.310(d)(6).

(ii) To account for stock fluctuations in abundance due to environmental variability, it may be necessary to design control rules that conserve spawning stock abundance during prolonged periods of poor recruitment.

(iii) Precautionary management is needed for species with special life history characteristics. For example, fishes with low frequency variability in recruitment or with rare large recruitments may require precautionary reduction in F. Species with life stages or behaviors that are highly vulnerable to fishing, such as spawning aggregation, might require reduction in F and perhaps a ban on fishing during these vulnerable periods.

CURRENT BSAI CRAB FISHERY MANAGEMENT STRATEGY

Major king and Tanner crab stocks in the Federal EEZ waters in the BSAI are managed under the Federal FMP for king and Tanner crab fisheries in the BSAI. The FMP is developed by the NPFMC under the MSFCMA. The MFMT (= F_{MSY}) and MSST (= 1/2 $SSB(F_{MSY})$ in most cases) in the MSY Control Rule are used as bench marks for determining the status of a stock. If the stock is overfished, a Target Control Rule is used for rebuilding the stock to the MSY producing level. Because of the lack of reliable F_{MSY} estimates for crab stocks, M is used as a surrogate for F_{MSY}. Furthermore, because of the lack of plausible M estimates for each crab stock, an M of 0.2 for the king crab group and an M of 0.3 for the *Chionoecetes* group have been adopted.

In addition, ADF&G on its own or with the help of NPFMC CPT has developed a harvest strategy for red and blue king, Tanner, and snow crab stocks in selected fisheries of the Bering Sea and Gulf of Alaska in accordance with the Alaska Board of Fisheries (Board) policy on king and Tanner crab resources management. The harvest strategies aim at keeping sufficient spawning biomass for stock productivity by controlling the removal of mature males. According to the Board's policy, harvest rate and GHL are determined for each exploitable portion of a stock, and threshold stock size level (mainly of mature portion) and threshold GHL for a few stocks (ADF&G 2001) are also estimated for assessing stock viability and manageability under continued fishing. The stock size thresholds levels are determined only for those stocks having sufficient fisheries and biological data and adequate stock assessment analysis. If the preseason stock size falls below the threshold levels, and in some fisheries, if the preseason estimates of GHL is lower than minimum acceptable GHL, the fishery is closed for the entire season. If it is above the threshold levels, a harvest rate that varies with the standing stock size is applied to calculate GHL. To avoid overharvest of legal males within the GHL, up to a maximum of 60% harvest of the estimated number of legal males is enforced in most fisheries (Pengilly and Schmidt 1995). Incidental mortality of crabs in other fisheries (trawl, fish pot, and dredge) is reduced by enforcing a maximum allowable crab bycatch percentage (of the crab abundance) in those fisheries and closed areas (ADF&G 2001; NPFMC 2001).

Currently, all BSAI king, Tanner, and snow crabs are managed under the Federal FMP along with the State harvest strategy. All the other crab stocks are managed by the State harvest strategy. Annual trawl surveys are conducted in Bering Sea federal waters by NMFS. ADF&G surveys cover mostly State waters. The trawl surveys determine crab stock abundance by sex, size, maturity, and shell age using an area swept method of analysis. Because trawl surveys are subject to sampling errors, CSA is used in some stocks to obtain better stock abundance estimates. For those stocks having long time series of length frequency and trawl survey abundance data (e.g., Bristol Bay red king crab), LBA is used for fine-tuning stock abundance estimates. The abundance estimates are used to compare the status of standing stock size with the Federal overfishing and State threshold levels for opening the fishery and to determine the GHL on an annual basis. Some crab stocks are not surveyed annually (e.g., the Norton Sound red king crab stock is surveyed triennially using trawl gear and annually using pot gear; the Aleutian Islands golden king crab stock is surveyed triennially by pot gear), while some others are not surveyed at all (e.g., deepwater grooved Tanner crab (*C. tanneri*) and triangular Tanner crab (*C. angulatus*) stocks). For those stocks having no annual stock abundance estimates, GHLs are determined based on either the very recent abundance estimates or historical average harvests. In addition, the current stock status of unsurveyed stocks is determined by FPA. The FPA involves examining CPUE, size, sex, maturity, and shell age compositions, amount of sublegal crab discards, amount of other crab bycatch, and prohibited area of fishing in the recently concluded fisheries.

Most BSAI crab fisheries are managed by sex, size, and season with a GHL determined from either stock biomass or long-term mean harvest and recent performance. In addition, fisheries performance within a season is monitored and, if the fishery is expected to exceed the GHL before the declared closure date, then the season is closed by an ADF&G Commissioner's emergency order. Only male crab at or above minimum legal size are allowed to be retained for marketing. Single sex harvest has been in effect since the late 1940's to protect mature females for sufficient recruit production. Specific fishing seasons are set to avoid harvesting crab during mating and molting (soft-shell) periods.

ALTERNATIVES CONSIDERED

Alternative 1. Status Quo. No revision to the 1999 crab overfishing definition (NPFMC 1999) would be made, and the definitions would not be updated in the FMP.

Alternative 2. (Preferred) Redefine some of the overfishing definitions and their analysis methods, and update those definitions and analysis methods in the FMP.

The 1999 crab overfishing definition revision (NPFMC 1999) was based on the MSFCMA or Revised National Standard 1 Guidelines (section 3.1.2). That revision redefined overfishing, OY, and MSY, and updated the FMP. Those definitions and analysis methods are grouped under Alternative 1 and the proposed new definitions and analysis methods are classified under Alternative 2 as follows:

OY

(a) Alternative 1

(i) OY Definition:

"The term "optimum," with respect to the yield from a fishery, means the amount of crab which (a) will provide the greatest overall benefit to the Nation, particularly with respect to food production and recreational opportunities, and taking into account the protection of marine ecosystems; (b) is prescribed as such on the basis of MSY from the fishery, as reduced by any relevant economic, social, or ecological factor; and (c) in the case of an overfished fishery, provides for rebuilding to a level consistent with producing the MSY in such fishery."

(ii) Estimation of OY

The BSAI crab regulatory process considered social (e.g., desire for stabilized economy) and economic factors (e.g., low marketability of females and small males) as well as biological (e.g., growth, mortality, abundance) factors in formulating harvest strategies and hence harvests reflected the OY concept. Crab in the BSAI are currently managed to optimize yield. As a result, the following set of Control Rules is already in operation to reduce MSY by appropriate factors.

(ii.a) no harvest of female crabs (sex restriction);

(ii.b) only crabs greater than or equal to a minimum size limit may be harvested (size restriction);

(ii.c) GHL estimated from exploitation rate strategy or fishery performance data;

(ii.d) non-retained catch of directed harvest; and

(ii.e) non-directed harvest including subsistence, sport, and bycatch.

(iii) Management Practice to Achieve OY Below MSY

The ADF&G in consultation with NMFS recommends appropriate management measures for a given year and geographical area consistent with the Board's policy on king and Tanner crab resource management, the FMP, the MSFCMA, and other State and Federal laws. In addition, the Board has established State harvest strategies that are consistent with the Board's policy on king and Tanner crab management (see section 4). The harvest strategies are aimed at minimizing the risk of overfishing and obtaining OY below MSY (NPFMC 1999).

(b) Alternative 2

The definition of OY for BSAI crab stocks under Alternative 1 has been defined in accordance with the NMFS National Standard 1 guidelines and complies with the MSFCMA. The above harvesting Control Rules optimize the yield while conserving the resources. Under Alternative 2, there is no change in both the definition and estimation method.

MSY

(a) Alternative 1

(i) MSY Definition

"The largest long-term average catch or yield [of crab] that can be taken from a stock or stock complex under prevailing ecological and environmental conditions."

(ii) Estimation of MSY

Several BSAI crab stocks have insufficient scientific data to estimate BRPs and stock dynamics are inadequately understood. The MSY is computed as the 15-year mean harvest at F_{MSY} (= M) from the biomass of the male and female portion of the mature population or total mature biomass (MB_n) of a stock. This choice resulted in lower MSY estimates for many stocks compared to those obtained by considering fully developed fishery periods defined in previous FMPs. The M is estimated by taking the largest crab size, converting this to age, and then computing M from Hoenig's (1983) M to longevity formula. An annual M value of 0.2 for king crabs and an M value of 0.3 for *Chionoecetes* species are used.

For BRP estimation, the 15-year period from 1983 to 1997 is considered adequate to satisfy both terms, "long-term" and "current environmental conditions," specified in the National Standard guidelines for estimating MSY. The CPT considered this period as representative of current environmental conditions because: (1) many crab stocks seem to have declined until the early 1980s and then stabilized; (2) finfish populations that increased sharply during the late 1970s (regime shift) seem to have stabilized somewhat by 1983; (3) recruitment from the generally high crab populations of the 1970s would have been evident or have dissipated by 1983; and (4) conditions in crab populations (particularly red and blue king crabs) are relatively stable over this period.

The MB_n for surveyed king crab stocks is computed by considering the catchability in survey trawl of each 5 mm carapace length (CL) size group of crabs, the proportion mature, the mean weight, and unadjusted survey index abundance for each size and sex group. The MB_n for surveyed Tanner and snow crabs is computed by considering the proportion mature, the mean weight, and unadjusted survey index of abundance (i.e., assuming a catchability value of 1) for each 5 mm carapace width (CW) size group of crabs and sex group. The MB_n for year n is taken as the sum of biomass over size and sex and considered as the annual average biomass available for a single stock. The sustainable yield for year n is estimated using the equation $SY_n = M \times MB_n$ and MSY is determined as the average of SY_n estimates over 15 years (1983–1997).

For stocks that are not surveyed or only have limited time series of survey data (i.e., data-poor stocks), MB_n is estimated in part using a ratio of legal biomass to mature biomass and corresponding utilization rate for representative stocks (NPFMC 1999). The MSY is estimated using this MB_n in the MSY estimation equation described in the previous paragraph. The Bristol Bay red, Pribilof Islands red and blue, and St. Matthew Island blue king crab stocks are selected to estimate the proxy mature biomass and utilization rates for the Western Aleutian Islands stock of red king crabs. These stocks are also used as the proxy stocks for the deep water king crabs: Aleutian Islands and Bering Sea scarlet king crabs (*Lithodes couesi*), and the Aleutian Islands, Pribilof Islands and St. Matthew Island golden king crab stocks. Both Tanner and snow crabs are chosen as being representative proxy stocks for the Eastern and Western Aleutian Islands Tanner crab stocks and deep water Tanner crabs (*C. tanneri* and C. angulatus) stocks in the Eastern and Western Aleutian Islands and Eastern Bering Sea.

(b) Alternative 2 (Preferred)

The MSY definition for BSAI crab stocks under Alternative 1 followed the NMFS National Standard 1 guidelines and complies with the MSFCMA. Therefore, the definition remains the same under Alternative 2. However, the estimation method requires modifications.

First, The MSY is estimated considering the total male and female mature crabs. Consequently, this MSY can be compared only with the total harvest of male and female crabs. However, only males are legally harvested in the BSAI directed crab fisheries. Therefore, for fishery performance determination, MSY should be estimated considering only legal male biomass, or at most, male mature biomass. Furthermore, because of spatial segregations and behavior of sexes, trawl survey catchability and pot fishery catchability for females are very low compared to the same size group of males for a number of crab stocks. For example, snow crab female catchability is much lower than that of sublegal males (J. Zheng, personal communication, Alaska Department of Fish and Game, Juneau). Therefore, estimation of mature female abundance will be somewhat biased and may introduce errors in the MSY estimation considering both sexes together.

Second, M is used as a proxy for F_{MSY} in estimating SY_n. Maintaining F at the M value is believed to produce yields near MSY (Alverson and Pereyra 1969; Gulland 1970). However, M is rarely equal to F_{MSY} under many different stock conditions (Francis 1974; Deriso 1982; Thompson 1992). It is also suggested to use M as an upper bound for stock management (Quinn and Deriso 1999). For the seven BSAI crab stock analyses (Bristol Bay red king, St. Matthew Island blue king, Pribilof Islands blue king, Eastern Aleutian Islands golden king, and Western Aleutian Islands golden king crabs; and Bering Sea Tanner and snow crabs) reported here, F_{MSY} was equal to M under very restricted condition and F_{MSY} could take any value—above, equal, or below M—depending on the steepness and overall shape of the S-R relationships and other vital parameters (see Figures 2–15). In this report the following formula relating F_{MSY} to M was established for any fish or shellfish stock (see Appendix A for the derivation), which required not only an M value but also various other parameter values, such as $W(F_{MSY})/W(0)$, $R(F_{MSY}) / R(0)$ and $ESB(0) / ESB(F_{MSY})$ ratios, to estimate F_{MSY}.

$$F_{MSY} = [\frac{W(F_{MSY})\, R(F_{MSY})\, (1-e^{-Z_{MSY}(\lambda - t_r)})}{X\, W(0)\, R(0)\, (1-e^{-M(\lambda - t_r)})} - 1]\, M \qquad (1)$$

For $F_{MSY} = M$, the fraction inside the braces of formula (1) should equal to 2, which may occur under a very restricted condition.

However, for harvest rate (a function of fishing mortality)– and biomass–based target and threshold estimations, the $E(F_{MSY})$ and $SSB(F_{MSY})/SSB(0)$ ratio were directly estimated using a combination of yield and $(ESB/R)_F$ approach with plausible ranges of values of crab growth, mortality, and reproduction parameters, and parameters of two well known S-R relationships, Beverton and Holt (1957) and Ricker (1954). The estimation procedures are explained in the Determination of Biological Reference Points for Seven BSAI Crab Stocks section.

Following this method, legal male MSY was estimated by the following approach:

The MSY was equal to the multiplication of the legal male portion of $SSB(F_{MSY})$ and $E(F_{MSY})$. The median value of $E(F_{MSY})$ estimates for plausible ranges of stock parameter values was taken as the MSY level harvest rate. The legal male $SSB(F_{MSY})$ in the stock was estimated from the median $SSB(F_{MSY})/SSB(0)$ ratio estimated at the same plausible ranges of stock parameter values, an estimate of virgin population, $SSB(0)$, during a selected period, and the proportion of mature males in the simulated $SSB(F_{MSY})$. The $SSB(0)$ was determined as the mean of top 20% of $SSB(F)$ estimates during this period. The estimation method was illustrated using Bristol Bay red king crab data with $SSB(0)$ determined from 1983–2001 biomass estimates in the Bristol Bay Red King Crab section.

The per-recruit analysis procedure cannot be applied to stocks lacking vital biological statistics needed for such an analysis including Tier 1 (data-poor) and some of Tier 2 (limited-data) stocks as defined in NPFMC (1999). Tier 1 stocks consist of Aleutian Islands Scarlet king crab, Bering Sea and Eastern Aleutian Islands triangle Tanner crab, and Aleutian Islands and Bering Sea grooved Tanner crab. The Tier 2 stocks are Aleutian Islands red king crab, Norton Sound red king crab, Aleutian Islands golden king crab, and Eastern Aleutian Islands Tanner crab. In this case, the best option is not to define any MSY and OY at all for these stocks because of limited data for per-recruit analysis. However, the National Standard Guideline does not allow this option and mandates the Councils to define an OY below MSY in a FMP based on the best available information on the stock or stock complex concerned. Under these circumstances, it is recommended to follow the Alternative 1 estimation procedure for Tier 1 and Tier 2 stocks. Note that the Alternative 1 procedure recommends estimating MSY from a proxy of mature biomass and a stock utilization rate considering $F_{MSY} = M$. The trends in $\log_{10}(F_{MSY}/M)$ for the seven crab stocks studied in this report suggested that $F_{MSY} > M$ for plausible extinction (S-R shape) parameter (τ) values for the two type of S-R relationships (Figures 2–15). This is more likely the case for the data-poor crab stocks as well. However, the MSY under Alternative 1 will most likely be an underestimate (NPFMC 1999).

Overfishing Definition and MSY Control Rule

(a) Alternative 1

(i) Definitions

"(i.a) Overfishing: The terms "overfishing" and "overfished" mean a rate or level of fishing mortality that jeopardizes the capacity of a fishery to produce MSY on a continuing basis. Overfishing is defined for king crab and Tanner crab stocks in the BSAI management area as any rate of fishing mortality in excess of the maximum fishing mortality threshold, F_{MSY} [MFMT as defined below] for a period of 1 year or more. Should the actual size of the stock in a given year fall below the minimum stock size threshold [MSST as defined below], the stock is considered overfished."

"(i.b) MFMT: The maximum fishing mortality threshold (MFMT) is defined by the MSY control rule [defined below], and is expressed as the fishing mortality rate. The MSY fishing mortality rate, $F_{MSY} = M$, a conservative natural mortality value set equal to 0.2 for all species of king crab, and 0.3 for all *Chionoecetes* species."

"(i.c) MSST: The minimum stock size threshold is whichever is greater: one-half of MSY stock size (defined below), or the minimum stock size at which rebuilding to the MSY level would be expected to occur within 10 years if the stock or stock complex were exploited at the MFMT. The MSST is expressed in terms of [total] mature biomass."

"(i.d) MSY control rule: A harvest strategy, which, if implemented, would be expected to result in a long-term average catch approximating MSY. The MSY control rule for king and Tanner crabs is the mature biomass of a stock under prevailing environmental conditions, or proxy thereof, exploited at a fishing mortality rate equal to a conservative estimate of natural mortality."

"(i.e) MSY stock size: The average size of the stock, measured in terms of [total] mature biomass, or a proxy thereof, under prevailing environmental conditions. It is the stock size that would be achieved under the MSY control rule. It is also the minimum standard for a rebuilding target when remedial management action is required."

(b) Alternative 2

The definition of, "Overfishing," "MFMT," and " MSST," are in accordance with the NMFS National Standard 1 guidelines and comply with the MSFCMA. Although the first sentence of the "MSY control rule" is in accordance with the National Standard guidelines, the subsequent sentence, interpreting the rule for BSAI king and Tanner crab stocks, is confusing. Furthermore, the justifications for equating F_{MSY} to M in the MFMT definition as well as in the MSY control rule, and equating MSY stock size to an average size of the total mature biomasses for 1983–1997 are questionable.

The relationship between F_{MSY} and M is explained in the previous section, which indicates that F_{MSY} is seldom equal to M. Therefore, for stocks with the availability of required biological parameters for per-recruit analysis (e.g., the seven BSAI crab stocks considered in this report), F_{MSY} can be directly estimated using the per-recruit analysis procedure. However, this procedure cannot be applied to stocks lacking vital statistics for per-recruit analysis (e.g., Tier 1 and some of Tier 2 stocks) to determine F_{MSY} directly. In this case, the best option available is not to define any threshold or target reference points for data-poor stocks. However, the National Standard Guideline does not allow this option and mandates the Councils to define the reference points in a FMP based on the best information available on the stock or stock complex concerned. Under these circumstances, an appropriate precautionary definition of MFMT is to equate F_{MSY} to M. Justification to use M for MFMT is provided under Alternative 2 in the MSY estimation section. Restrepo et al.'s (1998) recommendation to use 0.8 M or 0.75 M for F_{MSY} cannot be considered for data-poor crab stocks because the present analysis indicates that F_{MSY} is not bounded above by M.

Similar to the approaches suggested under Alternative 2 for MSY determination, the total $SSB(F_{MSY})$ (i.e., MSY stock size) can be estimated from the estimated median $SSB(F_{MSY})/SSB(0)$ ratio and an estimate of total $SSB(0)$ for a selected period. The selected period can be any length of time, not necessarily 1983–1997. Then, in the absence of more detailed analyses, a default MSST can be estimated as equivalent to $c \bullet SSB(F_{MSY})$ where $c = max\ (1\text{-}M,\ 0.5)$.

According to National Standard 1 guidelines, the MSY control rule fishing mortality is a continuous function of biomass. Since a number of BSAI crab stocks still lack necessary data for more detailed stock analyses, default segmented control rules are proposed. Thus, the default MSY control rule is redefined as follows:

It is the harvest strategy, which, if implemented, would be expected to result in a long-term average catch approximating MSY. Following Restrepo et al. (1998) and Restrepo and Powers (1999), the default MSY control rule for BSAI king and Tanner crabs is given by the following set of formulas:

$$
\begin{aligned}
&F(SSB) = F_{MSY} \bullet SSB / \ c \bullet SSB(F_{MSY}) && \text{for all} && SSB \le c \bullet SSB(F_{MSY}) \\
&F(SSB) = F_{MSY} && \text{for all} && SSB > c \bullet SSB(F_{MSY}) \qquad (2)
\end{aligned}
$$

where MSST = $c \bullet SSB(F_{MSY})$, c = max[(1-M), ½], and both F_{MSY} and $SSB(F_{MSY})$ are estimated from a constant-F control rule.

Harvesting under the above MSY control rule is expected to produce a long-term average catch approximating MSY under prevailing environmental condition.

In the BSAI crab stock management and rebuilding plans (under Alternative 1), c is set at 0.5, which may not be precautionary. Although king and Tanner crab (the latter group includes snow crab) M estimates are uncertain, they are likely to be below 0.5 (Zheng et al. 1995a, NPFMC 1999, Kruse et al. 2000). Therefore, the c values for MSST estimation should be 0.7 and 0.6 for the king (M = 0.3) and Tanner (M = 0.4) crab stocks, respectively.

Under Alternative 2, the F_{MSY} was estimated by the $(ESB/R)_F$ simulation procedure and the total $SSB(F_{MSY})$ was determined using the same simulation procedure with survey abundance estimates. In the BSAI crab fisheries management, a harvest rate is used instead of F. Thus, in the MSY and target control rules (sets of formulas (2) and (3)), $F(SSB)$ and F_{MSY} can be replaced by $E(F_{MSY})$ using equation (5). The $E(F_{MSY})$ estimation procedure is demonstrated using data for seven BSAI crab stocks and the $SSB(F_{MSY})$ estimation procedure is illustrated using only Bristol Bay red king crab data in the Determination of Biological Reference Points for Seven BSAI Crab Stocks section.

Target Control Rule Definition

(a) Alternative 1: not defined

(b) Alternative 2: The default target control rule is defined as follows:

It is the harvest strategy, which, if implemented, would be expected to result in a long-term average catch approximating OY under prevailing environmental condition. Following Restrepo et al. (1998), the default target control rule for BSAI king and Tanner crabs is given by the following set of formulas:

$$
\begin{aligned}
&F(SSB) = 0.75F_{MSY} \bullet SSB/[\,c \bullet SSB(F_{MSY})] && \text{for all} \quad SSB \le c \bullet SSB(F_{MSY}) \\
&F(SSB) = 0.75F_{MSY} && \text{for all} \quad SSB > c \bullet SSB(F_{MSY}) \qquad (3)
\end{aligned}
$$

Note that there are a number of ways of managing a fishery to achieve the target, so, this is one of many ways.

For a severely overfished stock, following Restrepo et al. (1998), the following set of formulas can be used for rebuilding purpose:

$$
\begin{aligned}
&F(SSB) = 0 && \text{for all} \quad SSB \le 0.5\ c \bullet SSB(F_{MSY}) \\
&F(SSB) = 0.75 \times 0.75F_{MSY} \bullet SSB/\ [c \bullet SSB(F_{MSY})] && \\
& && \text{for all} \quad 0.5\ c \bullet SSB(F_{MSY}) < SSB \le c \bullet SSB(F_{MSY}) \\
&F(SSB) = 0.75 \times 0.75F_{MSY} && \text{for all} \quad c \bullet SSB(F_{MSY}) < SSB \le SSB(F_{MSY}) \\
&F(SSB) = 0.75F_{MSY} && \text{for all} \quad SSB > SSB(F_{MSY}) \qquad (4)
\end{aligned}
$$

The MSY and target control rules and the rebuilding plan according to sets of equations (2), (3), and (4) are shown in Figure 1.

Whereas the MSY control rule can be used for stock status determination purposes, the target control rule can be used to obtain optimum yield from a stock. The rebuilding plan is a modification of the target control rule to rebuild a severely overfished stock.

DETERMINATION OF BIOLOGICAL REFERENCE POINTS FOR SEVEN BSAI CRAB STOCKS

F_{MSY}, $E(F_{MSY})$, and $SSB(F_{MSY})/SSB(0)$ Determination Method

Mace (1994) derived a set of formulas based on *SSB/R* to investigate the trends in various BRPs, including F_{MSY} and $SSB(F_{MSY})$, for finfish types of stock parameters under Beverton and Holt (1957) and Ricker (1954) *S-R* models. This procedure was extended to seven BSAI crab stocks to explore the trends in $E(F_{MSY})$, log $_{10}$ (F_{MSY}/M), and $SSB(F_{MSY})/SSB(0)$ ratio for different mortality values, male: female mating ratio, and *S-R* relationships. The $E(F_{MSY})$ formula modified from Gulland (1983) is as follows:

$$E(F_{MSY})=\left(\frac{F_{MSY}}{F_{MSY}+(M+BYM)\,\delta}\right)\left(1-e^{-(F_{MSY}+(M+BYM)\,\delta)}\right) \qquad (5)$$

The length-based method was used to simulate yield and $(ESB/R)_F$ as follows:

The simulation was started with 1,000 prerecruit-1 male crabs (one growth increment below recruit size, but mature) and 1,000 class-1 female crabs (one growth increment below the class-2 size, but mature) to estimate $(ESB/R)_F$ for the combined sexes to generate recruits and then yield from only male recruits. The females, which are not retained in the catch, were labeled as class-1 and class-2 size groups. The male crabs in each prerecruit-1 size interval may remain in the same size interval, or grow to higher size intervals as a result of annual molt followed by growth. Male crabs in any size interval will remain in the same size interval next year if they skip molt or molt with insufficient growth to move into a larger size interval. All female (red, blue, and golden) king crabs were assumed to molt annually (e.g., see Zheng et al. 1995a for red king crab); so, female crabs in any size interval will remain in the same size interval next year if they molt with insufficient growth to move into a larger size interval; otherwise, they will grow to a larger size group. On the other hand, all female

Chionoecetes crabs were assumed to undergo terminal molting when they reach maturity (e.g., see Otto 1998 for snow crab and Donaldson et al. 1981 for Tanner crab). So, the mature female crabs of this genus in any size group will remain in the same size group next year. The abundances in each size interval are also affected by mortality.

The length-based models used to capture these growth and mortality characteristics are given in Appendix B, which provides steps to calculate the equilibrium $(ESB/R)_F$, the basis of BRP estimation.

Recruitment was modeled using the following two well-known *S-R* models:

$$R(F) = \frac{\mathrm{ESB}(F)}{\alpha + \beta \bullet \mathrm{ESB}(F)} \qquad \text{(Beverton and Holt 1957)} \quad \text{and} \tag{6}$$

$$R(F) = \gamma \bullet \mathrm{ESB}(F)\ e^{-\theta\ \mathrm{ESB}(F)} \qquad \text{(Ricker 1954),} \tag{7}$$

Asymptotic (maximum) recruitment (R_{max}) for Beverton and Holt *S-R* relationship is $1/\beta$, and that for the Ricker *S-R* relationship is $\frac{\gamma e^{-1}}{\theta}$. R_{max} was set at 2,000 and equally divided between male and female crabs for per-recruit analysis.

Mace (1994) provided the extinction parameter, τ (which determines the slope near the origin and overall shape of *S-R*), as

$$\tau = \frac{(ESB/R)_{ESB=0}}{(ESB/R)_{F=0}}, \tag{8}$$

where $(ESB/R)_{ESB=0}$ is equal to α for the Beverton and Holt *S-R* model and $1/\gamma$ for the Ricker *S-R* model.

Therefore, for the Beverton and Holt *S-R* model,

$$\alpha = \tau \bullet (\mathrm{ESB/R})_{F=0}, \qquad \text{and} \tag{9}$$

$$\gamma = \frac{1}{\tau \bullet (\mathrm{ESB/R})_{\mathrm{F=0}}} \qquad \text{for the Ricker } S\text{-}R \text{ model.} \tag{10}$$

Thus, for a given τ and a fixed R_{max}, all parameters of the *S-R* relationships can be determined from an estimate of $(ESB/R)_{F=0}$.

For BRP estimation, the *R(F)* and various proportions were estimated from $(ESB/R)_F$ for a stochastic growth pattern and a range of constant mortality parameter values as follows:

$$\mathrm{R}(F) = \frac{(ESB/R)_F - \alpha}{\beta \bullet (ESB/R)_F} \qquad \text{(Beverton and Holt } S\text{-}R \text{ model),} \tag{11}$$

$$\mathrm{R}(F) = \frac{ln(\gamma \bullet (ESB/R)_F)}{\theta \bullet (ESB/R)_F} \qquad \text{(Ricker } S\text{-}R \text{ model),} \tag{12}$$

The *R(F)* (initial number of prerecruit-1 male and class-1 female crabs) was estimated from either equation (11) or (12) and was equally divided into males and females, and catch in numbers ($c(F)_t$) and weight ($y(F)_t$) during a time period *t* was generated from only male recruits using the following equations:

$$c(F)_t = \left(\frac{F}{F+(M+BYM)\,\delta}\right)\left(\sum_{j'=4}^{10} N(F)_{j',t}\right) e^{-M\,T}\left(1-e^{-(F+(M+BYM)\,\delta)}\right), \quad \text{and} \tag{13}$$

$$y(F)_t = \left(\frac{F}{F+(M+BYM)\,\delta}\right)\left(\sum_{j'=4}^{10} N(F)_{j',t} W_{l'}\right) e^{-M\,T}\left(1-e^{-(F+(M+BYM)\,\delta)}\right), \tag{14}$$

The total catch in numbers, *C(F)*, and weight, *Y(F)*, for the average fishery life span of the cohort, was obtained by:

$$C(F) = \sum_{t=t_r}^{\lambda} c(F)_t \tag{15}$$

$$Y(F) = \sum_{t=t_r}^{\lambda} y(F)_t \tag{16}$$

The F_{MSY} for a given set of growth and other mortality parameters (M, HM_i, and BYM) was determined by systematically searching for a maximum $Y(F)$ over F from 0.01 to 10 in 0.01 increments. The $E(F_{MSY})$ was determined using equation (5) at F_{MSY}.

The true mature stock biomass $SSB(F)$ was estimated as the sum of male and female total mean mature biomass generated from 1,000 prerecruit-1 male and 1,000 class-1 female crabs without adjusting for mating ratio. It was calculated using equations (B 24) to (B 29) without the "*effective MSSN/MSSN*" and "*effective FSSN/FSSN*" terms (see Appendix B). Thus, this $SSB(F)$ is the unconstrained (or nominal) total average spawning stock biomass that produced $R(F)$ for $Y(F)$ estimation. Unlike $ESB(F)$, estimation of $SSB(F)$ is straightforward for any stock and is useful for stock monitoring purposes. Therefore, the biomass-based BRP was estimated in terms of $SSB(F)$.

Crab sizes were grouped into 5-cm intervals for the analysis. The simulations were performed by VBA program for three levels of M, three levels of male to female mating ratio, two levels of h (hence HM_i) and BYM, one set of values of a mean and a standard deviation of growth increment for stochastic growth projection, and a range of values of τ, from 0.05 to 0.75 by 0.05 increments.

The male to female mean mating ratio was set at 1:1, 1:2, and 1:3. Based on a laboratory study, Paul and Paul (1997) suggested an optimum ratio of one legal-sized male to three multiparous females for red king crab population modeling purposes. Zheng and Kruse (1998) noted that a male is capable of mating with from 2 to 8 female Tanner crabs under the worst to the most ideal conditions, respectively. Mating ratios in other crab species are not well known, but presumably have similar patterns. Therefore, the above three sets of mean mating ratios were used across all king and Tanner crab species.

HM_i is a function of F, h, and catchabilty of sublegal males and females, while BYM is dependent on the bycatch rates in the non-directed crab fisheries and groundfish fisheries. The HM_i and BYM derivation formulas are given in Appendix B. For simplicity, size selectivity was ignored in the HM_i and BYM calculations. The prerecruit-1 male and the two classes of female abundances decline due to M, HM_i, and BYM; whereas, male fishery recruit and postrecruit abundances decline due to *F*, *M*, and *BYM*. For simplicity, these parameters were kept constant and equal among all stages, but varied to different levels in each simulation. The plausible *M*, *h*, and *BYM* values used for selecting threshold BRPs for the seven crab stocks are listed in Table 6.1. The *M* and *h* values were selected from recent literature for well-studied stocks and assumed reasonable values for data-poor stocks (red king crab: Zheng et al. 1997, Kruse et al. 2000; snow crab *h*: J. Zheng, personal communication, Alaska Department of Fish and Game, Juneau; Tanner crab: Zheng and Kruse 1999; St. Matthew Island blue king crab *h*: Zheng and Kruse 2000). The *BYM* were maximum values determined from the 1994-1999 bycatch weighted (by stock size) average harvest rates from all fisheries (NPFMC 2000).

The actual size distributions of prerecruit-1 male and class-1 female crabs may vary by year and are not well understood for all crab stocks. Therefore, the initial number of individuals (i.e., total prerecruit-1 and class-1 crabs) was equally distributed among the 5-mm carapace length (CL) size intervals within each stage. However, the distribution of subsequent growth increments at each molt was assumed to be normal with a constant mean and a standard deviation to determine growth proportion ($P_{l', l}$). There is no unique age for the initial stage because it is composed of various ages depending on individual growth histories. Hence a relative age of zero ($t_r = 0$) for the entire size range of prerecruit-1 males and class-1 females was assumed, and the male and female cohorts were tracked for 10 years ($\lambda = 10$). This allowed an approximate average cohort age of 15–16 years at the minimum in the fishery, assuming prerecruit-1 male and class-1 female crabs were 5–6 years old. In the case of the comparatively long-lived red king crab, which lives over 20 years, Alverson (1980) and Kruse et al. (2000) reported that very few crabs live longer than 15 years. Hence tracking the cohort for 10 years for BRP estimation is reasonable.

The δ was used in the simulation to generate both abundance and catch of male crabs, whereas *T* was used only to generate catch of male crabs. The mean estimate of δ for 1996–2000 fishing seasons (ADF&G 2001) and the mean value of *T* for 1995 to 1999 fishing seasons (R. Otto, personal communication, National Marine Fisheries Service, Kodiak) for the seven crab stocks are listed in Table 6.1.

The variation in τ provides varied steepness near the origin and overall shape of the two *S-R* curves. This τ range was assumed more than adequate for the BSAI crab stocks because it covered values from a high compensation level of 0.05 (survival from eggs to recruits at low stock sizes approximately 20 times that at the virgin size) to a very low compensation level of 0.75 (survival at low stock sizes about 1.33 times that at the virgin size). A number of king crabs in the BSAI have been in depressed stock status for a long time (ADF&G 2001) and it is prudent to consider them to be less resilient to overexploitation. Thus, a τ range of 0.3–0.5 was selected as appropriate for determining BRPs (M.S.M. Siddeek, unpublished data). Note that the lower limit, 0.3, was suggested by Mace and Sissenwine (1993) as an appropriate overfishing threshold for little-known stocks.

The $E(F_{MSY})$, $\log_{10}(F_{MSY}/M)$, and $SSB(F_{MSY})/SSB(0)$ were plotted against τ for various plausible combinations of M, h, and *BYM* to explore the trends in threshold BRPs in relation to various stock parameters and to determine plausible ranges of threshold values. The BRP results pertaining to overfishing definitions are explained below for each of the seven BSAI crab stocks.

Bristol Bay Red King Crab

The prerecruit-1 male crabs are those in the 120–134 mm CL size range; recruit and postrecruit crabs are in the 135–169 mm CL size range (Collie and Kruse 1998; Zheng et al. 1995a; Kruse et al. 2000). The mature female size range was arbitrarily divided into two classes: class-1, 90–99 mm CL; and class-2, 100–139 mm CL. Male crabs are fully mature by 120 mm CL (Zheng et al. 1995a). Approximately 50% of females are mature at 89 mm CL and 80% are mature at 95 mm CL (Otto et al. 1990); therefore, 90 mm CL was chosen as the knife-edge female maturity length (i.e., cut-off size for delineating maturity). The parameters required for BRP estimation are listed in Table 6.2a.

M was varied from 0.2 to 0.4 by 0.1 increments. HM_i was related to legal crab F (equation B 7) with the assumption that the catchability of sublegal male and female crabs was half that of the legal crabs (Zheng et al. 1997) and there was 20% handling mortality (h = 0.2) on captured and subsequently released sublegal crabs (Kruse et al. 2000). Handling mortality rate, *h*, was set at two levels, 0 and 0.2. The *BYM* was also set at two values, 0 and 0.01.

Results under the Beverton and Holt S-R model

Figure 2 depicts the trends in BRP ratios for different *M* and mating ratio values for *h* = 0.2 and *BYM* = 0.01. For the more likely values of *M* = 0.3, *h* = 0.2, *BYM* = 0.01, and τ range = 0.3–0.5, the median $SSB(F_{MSY})/SSB(0)$ ratios were 0.54, 0.69, and 0.50 for the mating ratios 1:1 to 1.3, 1:1, and 1:3, respectively (Table 6.2b). Thus, the median total spawning biomass at the MSY-producing level was about 50 to 69% of the virgin biomass. For the same scenario, the median $E(F_{MSY})$ values were 0.43, 0.21 and 0.50 for mating ratios1:1 to 1.3, 1:1, and 1:3, respectively (Table 6.2b).

Results under the Ricker S-R model

Figure 3 shows the trends in BRP ratios at different *M* and mating ratio values for *h* = 0.2 and *BYM* = 0.01. For the more likely scenario *M* = 0.3, *h* = 0.2, *BYM* = 0.01, and τ range = 0.3–0.5, the median $SSB(F_{MSY})/SSB(0)$ ratios were 0.50, 0.66, and 0.46 at mating ratios 1:1 to 1.3, 1:1, and 1:3, respectively (Table 6.2b); thus, the median total spawning biomass at the MSY-producing level was about 46 to 66% of the virgin biomass. Under the same set of conditions, the median $E(F_{MSY})$ values were 0.50, 0.24 and 0.60 at mating ratios 1:1 to 1.3, 1:1, and 1:3, respectively (Table 6.2b).

Conclusion

For both types of *S-R* models, higher mating ratios resulted in higher optimum harvest rates, but lower optimum biomass ratios. The simulation results did not change appreciably for different *M* values with higher *M* for females as reported by Zheng et al. (1997) (Table 6.2b). Considering the uncertainty in model specification and parameter estimates, following the precautionary management approach (Restrepo et al. 1998), the lowest median $E(F_{MSY})$ value of 0.43 and the highest median $SSB(F_{MSY})/SSB(0)$ ratio of 0.54 for the 1:1 to 1:3 mating ratio range (both obtained under the Beverton and Holt *S-R* model) were selected as threshold reference points for Bristol Bay red king crab stocks. When *SSB(F)* > MSST, the target harvest rate on legal males was $E(0.75F_{MSY})$ = 0.34 (34%).

$SSB(F_{MSY})$, MSST, and MSY Estimation

The simulation estimate of median $E(F_{MSY})$ = 0.43. The average of the upper 20% of total mature biomass during 1983–2001 (R. Otto, unpublished data, National Marine Fisheries Service, Kodiak), $SSB(0)$ = 132.98 million pounds (i.e., mean of 1989 (119.9), 1997 (130.7), 1998 (163.6), and 1999 (117.7) total mature biomass in million pounds). The simulation estimate of median (total) $SSB(F_{MSY})/SSB(0)$ ratio = 0.54. Therefore, MSY producing total mature biomass, $SSB(F_{MSY})$ = 0.54×132.98 = 71.81 million pounds. A default MSST = $(1-M)\times SSB(F_{MSY})$ = (1–0.3)×71.81 = 50.27 million pounds. The simulation estimate of the proportion of males in the total $SSB(F_{MSY})$ for the median sex ratio 1:2 = 0.64. Therefore, male $SSB(F_{MSY})$ = 0.64×71.81= 45.96 million pounds, and male MSY = 0.43×45.96 = 19.76 million pounds.

The MSY estimate for the 1983–2001 period by this method is approximately 10% higher than the value for the period 1983–1997, 17.9 million pounds, as reported in the 1999 review (NPFMC 1999). The probable reasons for the difference are: 1) two different periods were considered; 2) the present MSY estimate corresponded to mature males only whereas the previous estimate included both mature males and mature females; 3) different methods were used in the MSY estimation; and 4) the present MSY estimate was made using M = 0.3 whereas the previous estimate was made using M = 0.2. The MSST estimate by this method was also about 12% higher than the MSST value, 44.8 million pounds, as estimated by the Alternative 1 method (R. Otto, unpublished data, National Marine Fisheries Service, Kodiak). Reasons 3) and 4) above, and the different MSST estimation formula, $(1-M)\times SSB(F_{MSY})$, probably explain this difference.

Bering Sea Snow Crab

The prerecruit-1 male crabs are those in the 75–101 mm carapace width (CW) size range; recruit and postrecruit male crabs are those in the 102–124 mm CW size range. A non-terminal molt model for mature males and a terminal molt model for mature females were used in the simulations. Thus, for mature females, the annual cohort survival was estimated ignoring growth and the mature female size range was classified into a single class, 50–89 mm CW. Approximately 50% of males mature by 75 mm CW, and 50% of females mature by 50 mm CW (Otto 1998); therefore, 75 mm CW for males and 50 mm CW for females were chosen as respective knife-edge maturity lengths. The parameters required for BRP estimation are listed in Table 6.3a.

M was varied from 0.30 to 0.40 by 0.05 increments. HM_i was related to legal crab *F* (equation B 7) with the assumption that the catchability of sublegal male crabs was 0.56 and catchability of all female crabs was 0.0007 of that of the legal crabs (catchability coefficients were estimated from observer data on sublegal CPUE (ADF&G 2000 a, b)(see Appendix B for the derivation formula)) and there was 0.25 handling mortality (Zheng et al. 2002) on captured and subsequently released sublegal crabs. Two values of *h* were used, 0 and 0.25. *BYM* was also set at two levels, 0 and 0.01.

Results under the Beverton and Holt S-R model

Figure 4 depicts the trends in BRP ratios for different *M* and mating ratio values for *h* = 0.25 and *BYM* = 0.01. For the more likely values of *M* = 0.4, *h* = 0.25, *BYM* = 0.01, and τ range = 0.3–0.5, the median $SSB(F_{MSY})/SSB(0)$ ratios were 0.63, 0.69 and 0.57 for the mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.3b). Thus, the median total spawning biomass at the MSY producing level was about 57 to 69% of the virgin biomass. For the same scenario, the median $E(F_{MSY})$ values were 0.36, 0.27, and 0.48 for mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.3b).

Results under the Ricker S-R model

Figure 5 shows the trends in BRP ratios at different *M* and mating ratio values for *h* = 0.25 and *BYM* = 0.01. For the more likely scenario of *M* = 0.4, *h* = 0.25, *BYM* = 0.01, and τ range = 0.3–0.5, the median $SSB(F_{MSY})/SSB(0)$ ratios were 0.59, 0.66 and 0.53 at mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.3b); thus, the median total spawning biomass at the MSY producing level was about 53 to 66% of the virgin biomass. Under the same set of conditions, the median $E(F_{MSY})$ values were 0.44, 0.32, and 0.57 at mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.3b).

Conclusion

For both types of *S-R* models, higher mating ratios resulted in higher optimum harvest rates, but lower optimum biomass ratios. Considering the uncertainty in model specification and parameter estimates, following the precautionary management approach, the lowest median $E(F_{MSY})$ value of 0.36 and the highest median $SSB(F_{MSY})/SSB(0)$ ratio of 0.63 for the 1:1 to 1:3 mating ratio range (both obtained under the Beverton and Holt *S-R* model (Beverton and Holt 1957)) were selected as threshold reference points for Bering Sea snow crab stocks. When $SSB(F)$ > MSST, the target harvest rate on legal males was $E(0.75F_{MSY})$ = 0.28 (28%). Interestingly, the yield-per-recruit analysis with size and stage specific growth and mortality values provided a 0.1 harvest threshold (corresponding to $F_{0.1}$) on legal males at a harvest rate of 57% (Zheng et al. 2002), which was comparable to the $E(F_{MSY})$ value estimated for the mating ratio 1:3 under the Ricker *S-R* model (Ricker 1954).

Bering Sea Tanner Crab

The prerecruit-1 male crabs are those in the 120–137 mm CW size range; recruit and postrecruit crabs are those in the 138–169 mm CW size range. Females cease to grow as they reach maturity (Donaldson et al. 1980), therefore, the annual cohort survival of females was estimated ignoring growth, and the mature female size range was classified into a single class, 80–117 mm CW. Approximately 50% of males mature by 115 mm CW and 50% of females mature by 80 mm CW (Zheng et al. 1998); therefore, 80 mm CW was chosen as the knife-edge maturity length for females. The lower size limit of prerecruit-1 males, 120 mm CW, was higher than the 50% maturity length; thus, the majority of prerecruit-1 male crabs were fully mature. The parameters required for BRP estimation are listed in Table 6.4a.

M was varied from 0.30 to 0.40 by 0.05 increments. HM_i was related to legal crab F (equation B 7) with the assumption that the catchability of sublegal male crabs was 0.166 and the catchability of female crabs was 0.119 of that of the legal crabs (estimated as a weighted, by stock abundance, mean selectivity from Table 1 in Zheng and Kruse (1999)) and there was 0.2 handling mortality (Zheng et al. 1998) on captured and subsequently released sublegal crabs. Two values of h were used, 0 and 0.2. BYM was also set at two levels, 0 and 0.02.

Results under the Beverton and Holt S-R model

Figure 6 depicts the trends in BRP ratios for different *M* and mating ratio values for $h = 0.20$ and $BYM = 0.02$. For the more likely values of $M = 0.4$, $h = 0.20$, $BYM = 0.02$, and τ range = 0.3–0.5, the median $SSB(F_{MSY})/SSB(0)$ ratios were 0.66, 0.71, and 0.54 for the mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.4b). Thus, the median total spawning biomass at the MSY-producing level was about 54 to 71% of the virgin biomass. For the same scenario, the median $E(F_{MSY})$ values were 0.46, 0.33, and 0.88 for mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.4b).

Results under the Ricker S-R model

Figure 7 shows the trends in *BRP* ratios at different *M* and mating ratio values for $h = 0.20$ and $BYM = 0.02$. For the more likely scenario of $M = 0.4$, $h = 0.20$, $BYM = 0.02$, and τ range = 0.3–0.5, the median $SSB(F_{MSY})/SSB(0)$ ratios were 0.62, 0.69, and 0.54 at mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.4b); thus, the median total spawning biomass at the MSY producing level was about 54 to 69% of the virgin biomass. Under the same set of conditions, the median $E(F_{MSY})$ values were 0.57, 0.38 and 0.88 at mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.4b).

Conclusion

For both types of *S-R* models, higher mating ratios resulted in higher optimum harvest rates, but lower optimum biomass ratios. Considering the uncertainty in model specification and parameter estimates, following the precautionary management approach, the lowest median $E(F_{MSY})$ value of 0.46 and the highest median $SSB(F_{MSY})/SSB(0)$ ratio of 0.66 for the 1:1 to 1:3 mating ratio range (both obtained under Beverton and Holt *S-R* model (Beverton and Holt 1957)) were selected as threshold reference points for Bering Sea Tanner crab stocks. When $SSB(F) >$ MSST, the target harvest rate on legal males was $E(0.75F_{MSY}) = 0.37$ (37%).

St. Matthew Island Blue King Crab

The prerecruit-1 crabs are those in the 105–119 mm CL size range; recruit and postrecruit crabs are in the 120–154 mm CL size range. The mature female size range was arbitrarily divided into two classes: class-1, 80–89 mm CL; and class-2, 90–129 mm CL. Approximately 50% of males mature by 77 mm CL and 50% of females mature by 80.6 mm CL (Somerton and MacIntosh 1983); therefore, 80 mm CL was chosen as the knife-edge maturity length for the females. The lower size limit of prerecruit-1 males, 105 mm CL, was higher than the 50% maturity length for males; thus, the majority of the prerecruit-1 male crabs were fully mature. The parameters required for BRP estimation are listed in Table 6.5a.

M was varied from 0.2 to 0.4 by 0.1 increments. The HM_i was related to legal crab F (equation B 7) with the assumption that the catchability of sublegal male crabs was 0.665 (J. Zheng, personal communication, Alaska Department of Fish and Game, Juneau) and the catchability of female crabs was 0.4 (estimated from observer CPUE data) of that of the legal crabs and there was 0.2 proportion of handling mortality (Zheng and Kruse 2000) on captured and subsequently released sublegal crabs. Two values of h were used, 0 and 0.2. BYM was also set at two levels, 0 and 0.02. The majority of blue king crabs are biennial spawners (Otto and Cummiskey 1985); consequently, in each simulation, only half of the mature female survivors were considered for estimating $(ESB/R)_F$ according to different mating ratios.

Results under the Beverton and Holt S-R model

Figure 8 depicts the trends in BRP ratios for different M and mating ratio values for h = 0.20 and BYM = 0.02. For the more likely values of M = 0.3, h = 0.20, BYM = 0.02, and τ range = 0.3–0.5, the median $SSB(F_{MSY})/SSB(0)$ ratios were 0.54, 0.55, and 0.53 for the mating ratios 1;1 to 1:3, 1:1, and 1:3, respectively (Table 6.5b). Thus, the median total spawning biomass at the MSY producing level was about 53 to 55% of the virgin biomass. For the same scenario, the median $E(F_{MSY})$ values were 0.43, 0.40, and 0.44 for mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.5b).

Results under the Ricker S-R model

Figure 9 shows the trends in BRP ratios at different M and mating ratio values for h = 0.20 and BYM = 0.02. For the more likely scenario M = 0.3, h = 0.20, BYM = 0.02, and τ range = 0.3–0.5, the median $SSB(F_{MSY})/SSB(0)$ ratios were 0.50, 0.52, and 0.49 at mating ratios 1:1 to

1:3, 1:1, and 1:3, respectively (Table 6.5b); thus, the median total spawning biomass at the MSY-producing level was about 49 to 52% of the virgin biomass. Under the same set of conditions, the median $E(F_{MSY})$ values were 0.51, 0.48, and 0.53 at mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.5b).

Conclusion

For both types of *S-R* models, higher mating ratios resulted in higher optimum harvest rates, but lower optimum biomass ratios. Considering the uncertainty in model specification and parameter estimates, following the precautionary management approach, the lowest median $E(F_{MSY})$ value of 0.43 and the highest median $SSB(F_{MSY})/SSB(0)$ ratio of 0.54 for the 1:1 to 1:3 mating ratio range (both obtained under the Beverton and Holt *S-R* model (Beverton and Holt 1957)) were selected as threshold reference points for St. Matthew Island blue king crab stocks. When $SSB(F)$ > MSST, the target harvest rate on legal males was $E(0.75F_{MSY})$ = 0.34 (34%).

Pribilof Islands Blue King Crab

The prerecruit-1 male crabs are those in the 120–134 mm CL size range; recruit and postrecruit crabs are those in the 135–169 mm CL size range. The mature female size range was arbitrarily divided into two classes: class-1, 95–104 mm CL; and class-2, 105–144 mm CL. Approximately 50% of males mature by 108 mm CL and 50% of females mature by 96.3 mm CL (Somerton and MacIntosh 1983); therefore, 95 mm CL was chosen as the knife-edge maturity length for females. The lower size limit of prerecruit-1 males, 120 mm CL, was higher than the 50% maturity length for males; thus, the majority of prerecruit-1 male crabs were fully mature. The parameters required for BRP estimation are listed in Table 6.6a.

M was varied from 0.2 to 0.4 by 0.1 increments. The HM_i was related to legal crab *F* (equation B 7) with the assumption that the catchability of sublegal male crabs was 0.665 and the catchability of female crabs was 0.4 of that of the legal crabs and there is 20% handling mortality on sublegal crabs (St. Matthew Island blue king crab sublegal catchability and *h* were assumed). The *BYM* value from St. Matthew Island blue king crab was used. Two values of *h* were used, 0 and 0.2. *BYM* was also set at two levels, 0 and 0.02. The majority of blue king crabs are biennial spawners; consequently, in the simulations, only half of the mature female survivors were considered for estimating $(ESB/R)_F$ according to different mating ratios.

Results under the Beverton and Holt S-R model

Figure 10 depicts the trends in BRP ratios for different M and mating ratio values for h = 0.2 and BYM = 0.02. For the more likely values of M = 0.3, h = 0.2, BYM = 0.02, and τ range = 0.3–0.5, the median $SSB(F_{MSY})/SSB(0)$ ratios were 0.53, 0.54, and 0.52 for the mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.6b). Thus, the median total spawning biomass at the MSY producing level was about 52 to 54% of the virgin biomass. For the same scenario, the median $E(F_{MSY})$ values were 0.44, 0.41, and 0.45 for mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.6b).

Results under the Ricker S-R model

Figure 11 shows the trends in BRP ratios at different M and mating ratio values for h = 0.2 and BYM = 0.02. For the more likely scenario M = 0.3, h = 0.2, BYM = 0.02, and τ range = 0.3–0.5, the median $SSB(F_{MSY})/SSB(0)$ ratios were 0.50, 0.51, and 0.49 at mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.6b); thus, the median total spawning biomass at the MSY producing level was about 49 to 51% of the virgin biomass. Under the same set of conditions, the median $E(F_{MSY})$ values were 0.50, 0.47, and 0.52 at mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.6b).

Conclusion

For both types of *S-R* models, higher mating ratios resulted in higher optimum harvest rates, but lower optimum biomass ratios. The BRP threshold estimates were similar to those for the St. Matthew blue king crabs, differing only by a single percent. Considering the uncertainty in model specification and parameter estimates, following the precautionary management approach, the lowest median $E(F_{MSY})$ value of 0.44 and the highest median $SSB(F_{MSY})/SSB(0)$ ratio of 0.53 for the 1:1 to 1:3 mating ratio range (both obtained under the Beverton and Holt *S-R* model (Beverton and Holt 1957)) were selected as threshold reference points for Pribilof

Islands blue king crab stocks. When *SSB(F)* > MSST, the target harvest rate on legal males was $E(0.75F_{MSY}) = 0.35$ (35%).

Western Aleutian Islands Golden King Crab

The prerecruit-1 male crabs are those in the 121–137 mm CL size range; recruit and postrecruit male crabs are in the 138–167 mm CL size range. The mature female size range was arbitrarily divided into two classes: class-1, 107–116 mm CL; and class-2, 117–156 mm CL. Approximately 50% of males mature by 120.8 mm CL (Otto and Cummiskey 1985) and 50% of females mature by 106.7 mm CL (Blau et al. 1998); therefore, 121 mm CL for males and 107 mm CL for females were chosen as the knife-edge maturity lengths. The parameters required for BRP estimation are listed in Table 6.7a.

M was varied from 0.2 to 0.4 by 0.1 increments. HM_i was related to legal crab *F* (equation B 7) with the assumption that the catchability of sublegal male and the catchability of female crabs were 0.5 and there was 0.2 handling mortality on sublegal crabs (Bristol Bay red king crab sublegal catchability and *h* were used). *BYM* value from Bristol Bay red king crab was used. Two *h* values, 0 and 0.2, were used. The *BYM* was also set at two values, 0 and 0.01.

Results under the Beverton and Holt S-R model

Figure 12 depicts the trends in BRP ratios for different *M* and mating ratio values for $h = 0.2$ and $BYM = 0.01$. For the more likely values of $M = 0.3$, $h = 0.2$, $BYM = 0.01$, and τ range = 0.3–0.5, the median $SSB(F_{MSY})/SSB(0)$ ratios were 0.56, 0.71, and 0.53 for the mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.7b). Thus, the median total spawning biomass at the MSY producing level was about 53 to 71% of the virgin biomass. For the same scenario, the median $E(F_{MSY})$ values were 0.43, 0.20, and 0.51 for mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.7b).

Results under the Ricker S-R model

Figure 13 shows the trends in BRP ratios at different *M* and mating ratio values for $h = 0.2$ and $BYM = 0.01$. For the more likely scenario $M = 0.3$, $h = 0.2$, $BYM = 0.01$, and τ range = 0.3–0.5, the median $SSB(F_{MSY})/SSB(0)$ ratios were 0.52, 0.68, and 0.39 at mating ratios 1:1 to

1:3, 1:1, and 1:3, respectively (Table 6.7b); thus, the median total spawning biomass at the MSY-producing level was about 39 to 68% of the virgin biomass. Under the same set of conditions, the median $E(F_{MSY})$ values were 0.52, 0.23, and 0.97 at mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.7b).

Conclusion

For both types of *S-R* models, higher mating ratios resulted in higher optimum harvest rates, but lower optimum biomass ratios. Considering the uncertainty in model specification and parameter estimates, following the precautionary management approach, the lowest median $E(F_{MSY})$ value of 0.43 and the highest median $SSB(F_{MSY})/SSB(0)$ ratio of 0.56 for the 1:1 to 1:3 mating ratio range (both obtained under the Beverton and Holt *S-R* model (Beverton and Holt 1957)) were selected as threshold reference points for Western Aleutian Islands golden king crab stocks. When $SSB(F)$ > MSST, the target harvest rate on legal males was $E(0.75F_{MSY})$ = 0.35 (35%).

Eastern Aleutian Islands Golden King Crab

The same size ranges considered in the Western Aleutian Islands golden king crab stock analysis were considered for the Eastern Aleutian Islands golden king crab male and female cohorts. The parameters required for BRP estimation are listed in Table 6.7a.

M was varied from 0.2 to 0.4 by 0.1 increments. HM_i was related to legal crab F (equation B 7) with the assumption that the catchability of sublegal male and the catchability of female crabs were 0.5 and there was 0.2 handling mortality on sublegal crabs (assumed to be same as that of the Western Aleutian Island golden king crab stock). The *BYM* was the same value as that of the Western Aleutian Islands stock. Two h values, 0 and 0.2, were used. *BYM* was also set at two levels, 0 and 0.01.

Results under the Beverton and Holt S-R model

Figure 14 depicts the trends in BRP ratios for different M and mating ratio values for h = 0.2 and *BYM* = 0.01. For the more likely values of M = 0.3, h = 0.2, *BYM* = 0.01, and τ range = 0.3–0.5, the median $SSB(F_{MSY})/SSB(0)$ ratios were 0.57, 0.71, and 0.54 for the mating ratios

1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.8). Thus, the median total spawning biomass at the MSY-producing level was about 54 to 71% of the virgin biomass. For the same scenario, the median *E*(F_{MSY}) values were 0.47, 0.22, and 0.55 for mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.8).

Results under the Ricker S-R model

Figure 15 shows the trends in BRP ratios at different *M* and mating ratio values for *h* = 0.2 and *BYM* = 0.01. For the more likely scenario *M* = 0.3, *h* = 0.2, *BYM* = 0.01, and τ range = 0.3–0.5, the median *SSB*(F_{MSY})/*SSB(0)* ratios were 0.53, 0.69, and 0.49 at mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.8); thus, the median total spawning biomass at the MSY producing level was about 49 to 69% of the virgin biomass. Under the same set of conditions, the median *E*(F_{MSY}) values were 0.55, 0.25, and 0.67 at mating ratios 1:1 to 1:3, 1:1, and 1:3, respectively (Table 6.8).

Conclusion

For both types of *S-R* models, higher mating ratios resulted in higher optimum harvest rates, but lower optimum biomass ratios. The BRP threshold estimates differed between the Western and the Eastern stocks, but significant differences were observed at the mating ratio 1:3, especially under Ricker *S-R* model (Ricker 1954). This was perhaps due to the shorter fishing time period observed in the Eastern Aleutian Islands fishery than in the Western fishery. Considering the uncertainty in model specification and parameter estimates, following the precautionary management approach, the lowest median *E*(F_{MSY}) value of 0.47 and the highest median *SSB*(F_{MSY})/*SSB(0)* value of 0.57 for the 1:1 to 1:3 mating ratio range (both obtained under the Beverton and Holt *S-R* model (Beverton and Holt 1957)) were selected as threshold reference points for Eastern Aleutian Islands golden king crab stocks. When *SSB(F)* > MSST, the target harvest rate on legal males was $E(0.75F_{MSY})$ = 0.38 (38%).

DISCUSSION

The F_{MSY} formula as a function of *M* established in this paper was based on a general, age-specific cohort growth (in weight) model incorporated into an age-specific cohort survival model (Beverton and Holt 1957). This equation was applicable to any fisheries resource. The F_{MSY} estimates for the seven BSAI crab stocks suggested F_{MSY} to be higher than M under a number of feasible conditions and less than or equal to M for a few restricted conditions when the mating ratio was 1:1 and the τ value was very high. A number of investigations based on teleost fish population parameters concluded M to be an upper limit for F_{MSY} (e.g., Deriso 1982; Quinn and Deriso 1999). This was not the general case for the BSAI crab stocks. Differences in growth pattern and mating behavior and the single-sex exploitation strategy have made crab stock dynamics quite different from that of teleosts, and one should be cautious when selecting the same teleost-based BRP values to formulate crab-harvesting strategies.

Reasonably close estimates of F_{MSY} (equivalent harvesting rate $E(F_{MSY})$) and mature stock biomass at F_{MSY} for a stock would be ideal to formulate an optimum harvesting strategy. If the *S-R* relationship, growth increment, molting probability, natural mortality, handling mortality, and bycatch mortality were known, this could be achieved. The exact *S-R* model could be used in the simulation to determine $E(F_{MSY})$ and $SSB(F_{MSY})/SSB(0)$ ratios. The latter, along with an estimate of maximum $SSB(F)$ (or a median or a mean value from a certain number of large $SSB(F)$ estimates) during a given environmental period, could be used to estimate $SSB(F_{MSY})$. However, most stocks lack necessary biological and fisheries information to establish a *S-R* relationship. This was the case for a number of crab stocks in the BSAI. The best option under this circumstance was to consider a few well-known *S-R* models with a narrow, but appropriate, variation in τ to obtain a plausible range of shapes of *S-R* curves, to get a reasonably narrow range of $E(F_{MSY})$ and $SSB(F_{MSY})/SSB(0)$ ratios. Thus, the length-based simulations considered two well-known *S-R* models: Beverton and Holt (Beverton and Holt 1957) and Ricker (Ricker 1954) with a τ range = 0.05–0.75 for investigating the trends in $\log_{10}(F_{MSY}/M)$, $E(F_{MSY})$, and $SSB(F_{MSY})/SSB(0)$. A still narrower, but plausible, τ range = 0.3–0.5 was considered to estimate narrow ranges of $E(F_{MSY})$ and $SSB(F_{MSY})/SSB(0)$ ratios. The mating ratio, which has a profound effect on recruitment, has not been investigated for many crab stocks. However, based on a laboratory study, Paul and Paul (1997) suggested an average mating ratio of 1:3 for the red king crab for modeling purposes. Because of uncertainty in the mating ratio parameter, the median estimates of

$E(F_{MSY})$ and $SSB(F_{MSY})/SSB(0)$ were obtained considering three mating ratios, 1:1, 1:2, and 1:3.

A number of king crabs in the BSAI were in depressed stock status for a long period of time (ADF&G 2001) and it is prudent to consider them to be less resilient to overexploitation. Thus, the choice of the τ range of 0.3–0.5 was appropriate. Note that the lower limit, 0.3, was suggested as an appropriate default overfishing threshold value for little-known stocks by Mace and Sissenwine (1993). Although the τ range for exploration was directly borrowed from a teleost-type modeling investigation by Mace (1994), it covered a reasonably wide range of steepness (and shape) of the Beverton and Holt (Beverton and Holt 1957) and Ricker (Ricker 1954) *S-R* curves that could be expected in a crab *S-R* relationship.

The major feature of the BSAI crab harvest strategy was the formulation of a GHL. This was calculated by multiplying the mature male biomass by a predetermined harvest rate (Kruse et al. 2000). Therefore, $E(F_{MSY})$ was a more useful parameter to focus on than F_{MSY}. According to the MSFCMA, the $E(F_{MSY})$ was a limit reference point. Consequently, the selected $E(F_{MSY})$ ranges should be treated as upper limits, and the target harvest rates should be set at lower levels to provide a buffer against overshooting $E(F_{MSY})$, perhaps at $E(0.75F_{MSY})$ when the stocks are near or above the MSY producing levels, and reduced further by a proportion of current stock biomass over MSY producing stock biomass when they are below MSY-producing levels (Restrepo and Powers 1999). This procedure was followed in some BSAI crab rebuilding plans (e.g., snow crab rebuilding strategy (Zheng et al. 2002)). Note that the 25% reduction in the fishing mortality rate was sufficient or not depending on a number of factors, particularly on uncertainty in assessment (Restrepo and Powers 1999). The $E(F_{MSY})$ and $SSB(F_{MSY})/SSB(0)$ varied with increasing M and τ at a given mating ratio at plausible HM_i and BYM values for both types of *S-R* models. Consequently, a narrow τ range was required to estimate plausible $E(F_{MSY})$ and $SSB(F_{MSY})/SSB(0)$ ranges for a more likely set of M, HM_i, BYM, and mating ratio values.

Although other per-recruit based BRPs, such as $F_{30\%}$ to $F_{60\%}$, with higher percentages corresponding to stocks with less resilience to fishing or environmental pressure (Restrepo and Powers 1999), a traffic light approach (Caddy 2002), wherein a "basket" of suitable threshold reference points is used to detect the danger (or red light) zone by accumulating bad points when the BRP is infringed, or an entirely different approach of determining BRPs based on spawner escapement goal might be equally good or better for crab management, this report did not attempt to identify them. The BRP estimation procedure considered only a single minimum legal size limit for each crab stock. Furthermore, all mortality parameters were treated as constants within respective stages of crabs and the growth increment probability model was assumed normal. These simplified assumptions were needed because the prime objective of this report was to develop crab-specific BRP estimation methods that could be applied to a wide range of crab stocks, especially the data-poor stocks. To improve the per-recruit method presented in this report, future research could focus on incorporating sex, size, and shell age specific mortality; performing sensitivity analysis of BRPs to varying minimum legal size limits; and determining BRPs based on appropriate levels of spawner escapement.

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APPENDIX A: DERIVATION OF F_{MSY} TO M RELATIONSHIP

The following assumptions were made in the derivation:

1. Constant instantaneous fishing (F) and natural (M) mortality over postrecruit ages.
2. Knife-edge selection occurs, once per year, at the recruitment age, t_r, and the age-at-first-capture is equal to the age-at-recruitment.
3. Weight at any age, w_t, is independent of the size at that age.
4. The stock is in a steady state determined by F and a whole or a constant proportion of the stock produces recruits.

Following Francis (1974) and Thompson (1992), the numbers, $N_t(F)$, of individuals in a cohort at age t for a given fishing mortality rate, F, can be written as:

$$N_t(F) = R(F)e^{-Z(t-t_r)}, \tag{A 1}$$

the corresponding cohort biomass, $B_t(F)$, can be written as:

$$B_t(F) = w_t R(F)e^{-Z(t-t_r)}, \tag{A 2}$$

The steady state exploitable stock numbers, $N(F)$, during a year when the exploitable stock (of age $\geq t_r$) is harvested at F is the sum of average numbers of each age class (or cohort) in the stock exploited at the same fishing mortality rate, F, during that year, and can be written as:

$$N(F) = \sum_{a=t_r}^{\lambda} \frac{\int_{t=a}^{a+1} N_t(F)dt}{\int_{t=a}^{a+1} dt} = R(F)\int_{t=t_r}^{\lambda} e^{-Z(t-t_r)}dt\,. \tag{A 3}$$

The corresponding steady state exploitable stock biomass, $B(F)$, is

$$B(F) = \sum_{a=t_r}^{\lambda} \frac{\int_{t=a}^{a+1} B_t(F)dt}{\int_{t=a}^{a+1} dt} = R(F)\int_{t=t_r}^{\lambda} w_t\, e^{-Z(t-t_r)}dt\,. \tag{A4}$$

The mean weight of individuals, *W(F)*, in the steady state stock exploited at *F* in a given year is

$$W(F) = \frac{B(F)}{N(F)} = \frac{R(F) \int_{t=t_r}^{\lambda} w_t \, e^{-Z(t-t_r)} dt}{R(F) \int_{t=t_r}^{\lambda} e^{-Z(t-t_r)}} = \frac{Z \int_{t=t_r}^{\lambda} w_t \, e^{-Z(t-t_r)} dt}{(1-e^{-Z(\lambda-t_r)})} \, . \qquad \text{(A 5)}$$

Therefore, combining (A 4) and (A 5), the following relationship is obtained:

$$B(F) = \frac{R(F) W(F)(1-e^{-Z(\lambda-t_r)})}{Z} \, . \qquad \text{(A 6)}$$

The virgin steady state stock biomass, *B(0)*, is then

$$B(0) = \frac{R(0) W(0)(1-e^{-M(\lambda-t_r)})}{M} \, . \qquad \text{(A 7)}$$

The maximum sustainable yield (MSY) occurs at a fraction, *X*, of the virgin stock biomass and the MSY producing equilibrium biomass, $B(F_{MSY})$, can be expressed as

$$B(F_{MSY}) = X \, B(0) = X \, \frac{R(0) W(0)(1-e^{-M(\lambda-t_r)})}{M} \, . \qquad \text{(A 8)}$$

From equation (A 6), it can also be written as

$$B(F_{MSY}) = \frac{R(F_{MSY}) W(F_{MSY})(1-e^{-Z_{MSY}(\lambda-t_r)})}{Z_{MSY}} \, . \qquad \text{(A 9)}$$

The following F_{MSY} to *M* relationship can be established from equations (A 8) and (A 9):

$$F_{MSY} = [\frac{W(F_{MSY}) \, R(F_{MSY}) \, (1-e^{-Z_{MSY}(\lambda-t_r)})}{X \, W(0) R(0)(1-e^{-M(\lambda-t_r)})} - 1] \, M \, . \qquad \text{(A 10)}$$

Note that in the text, the biomass (*B(F)*) that produces *R(F)* is referred to as *ESB(F)*.

APPENDIX B. CALCULATION STEPS TO DETERMINE EFFECTIVE SPAWNING STOCK BIOMASS -PER-RECRUIT $(ESB/R)_F$

The following assumptions were made to simplify the derivation:

1. Mortality takes place immediately after growth.
2. All female red king crab molt annually, but males molt with a size-dependent molt probability.
3. Instantaneous natural mortality, *M*, and bycatch mortality, *BYM*, are constant and independent of size and sex.
4. Instantaneous fishing mortality, *F*, is constant and independent of size.
5. Instantaneous handling mortality, *HM*, is constant and independent of size.
6. Recruits generated from *S-R* models for per-recruit analysis have 1:1 sex ratio.

The prerecruit-1 male group consisted of *l* intervals (for majority of the BSAI crab stocks, *l* =1 to 3). The following models were applied to these size intervals. In the analysis, each type of mortality was assumed constant irrespective of size, maturity, and shell-age conditions; thus, separate survival formulas for new shell and old shell crabs were not needed.

When *l* = 1,

$$N(0)_{l,t+1} = N(0)_{l,t}\,(m_l P_{l,l} + 1 - m_l)e^{-(M + HM_1\delta + BYM)}. \qquad \text{(B 1)}$$

The equation (B 1) is based on a simple cohort decline formula $N(0)_{l,t+1} = N(0)_{l,t}\, e^{-Z}$ with $N(0)_{l,t}$ adjusted (by the terms inside the braces immediately after $N(0)_{l,t}$) for proportion of crabs in size class *l* remaining in the same size class as a result of molting (m_l), but with insufficient growth ($P_{l,l}$) to move in to a higher size group, and proportion of non molting ($1-m_l$) crabs.

when l = 1,

when *l* >1,

$$N_{l,t+1} = \left[\sum_{l'=1}^{l-1} N_{l',t}\, m_{l'}\, P_{l',l} + N_{l,t} (m_l\, P_{l,l} + (1 - m_l)) \right] e^{-(M + HM_l\, \delta + BYM)}. \qquad \text{(B 2)}$$

The equation (B 2) is based on $N(0)_{l,t+1} = N(0)_{l,t}\, e^{-Z}$ with $N(0)_{l,t}$ comprised of two components (the terms inside the square brackets): 1) the sum of the number of crabs at lower size classes (l') that enter the size class l as a result of molting ($m_{l'}$) and growing ($P_{l',l}$), and (2) number of crabs remaining in the same size class l as a result of molting (m_l), but with insufficient growth ($P_{l,l}$) to move in to a higher size group, and non molting (1-m_l) number of crabs. The equations (B 3) and (B 4) can be explained in a similar way.

Male recruit and postrecruit groups comprised of l intervals (for majority of the cases, l = 4–10). Assuming that prerecruit-1 comprised of 3 intervals, and recruit and postrecruit stages consisted of 7 intervals, the following models are applied to these size intervals:

when $t+1$ = 1,

$$N(0)_{l,t+1} = \sum_{l'=1}^{3} N(0)_{l',t}\, m_{l'}\, P_{l',l}\; e^{-(M + HM_1\, \delta + BYM)}, \text{ and} \qquad \text{(B 3)}$$

when $t+1 \geq 2$,

$$N(F)_{l,t+1} = \sum_{l'=1}^{3} N(0)_{l',t}\, m_{l'}\, P_{l',l}\; e^{-(M + HM_1\, \delta + BYM)} + \left[\sum_{l'=4}^{l-1} N(F)_{l',t}\, m_{l'}\, P_{l',l} + N(F)_{l,t} (m_l\, P_{l,l} + 1 - m_l) \right] e^{-(M + F + BYM)}. \qquad \text{(B 4)}$$

In most cases, female class-1 is comprised of 2 intervals, and class-2 consisted of 8 intervals. The corresponding models for these size intervals are:

when $t+1$ = 1,

$$N(0)_{l,t+1} = \sum_{l'=1}^{2} N(0)_{l',t}\, P_{l',l}\; e^{-(M + HM_2\, \delta + BYM)}, \quad \text{and} \qquad \text{(B 5)}$$

when $t+1 \geq 2$,

$$N(0)_{l,t+1} = \sum_{l'=1}^{l} N(0)_{l',t} \, P_{l',l} \, e^{-(M + HM_2 \delta + BYM)} . \qquad \text{(B 6)}$$

The equations (B 5 and B 6) are also based on $N(0)_{l,t+1} = N(0)_{l,t} \, e^{-Z}$ with $N(0)_{l,t}$ equal to the sum of numbers of crabs at lower size classes (l') that enter the size class l as a result of annual growth ($P_{l',l}$) with a molting probability of one.

The HM_i was defined as a function of F, ignoring M and BYM as follows:

$$1 - e^{-HM_i \delta} = q_i h (1 - e^{-F}) .$$

Where q_i = sublegal crab catchability (i = 1 for male, and i = 2 for female), and others are defined in the list of notations in Appendix C.

Therefore,

$$HM_i = -\frac{1}{\delta} ln(1 - q_i h(1 - e^{-F})), \text{ and} \qquad \text{(B 7)}$$

$$BYM = -ln(1 - WAM) \qquad \text{(B 8)}$$

where WAM = weighted (by crab stock abundance) average mortality proportion of crab bycatch in all fisheries estimated from 1994–1999 data (NPFMC 2000). The following BYM estimates were obtained for four BSAI crab stocks:

Bristol Bay red king crab: 0.003,
Bering Sea Tanner crab: 0.0207,
Bering Sea snow crab: 0.0033, and
St. Matthew Island blue king crab: 0.0256.

Based on the above BYM estimate, an arbitrary maximum BYM value is set for each stock in the simulation analysis (Table 6.1).

The q_i's were obtained from published literature for the majority of the BSAI stocks considered in the analysis. However, in the absence of published estimates for a few stocks, e.g., St. Matthew Island female blue king crab, they were estimated using 1998 and 1999 observer CPUE data (ADF&G 2000 a,b) by the following approximate formulas:

$$CPUE_{Leg} = q_{Leg} N_{PreRec1} e^{-Z_2} (1 - e^{-Z_1}) / Z_1 \quad , \tag{B 9}$$

$$CPUE_{PreRec1} = q_{PreRec1} N_{PreRec1} (1 - e^{-Z_2}) / Z_2 \text{, and} \tag{B 10}$$

$$CPUE_{Female} = q_{Female} N_{Female} (1 - e^{-Z_2}) / Z_2 . \tag{B 11}$$

Assuming $N_{PreRec1} = N_{Female}$ (abundance in numbers), and sublegal total mortality (Z_2) is the same for both males and females,

$$q_{PreRec1} \approx q_{Leg} \frac{CPUE_{PreRec1}}{CPUE_{Leg}} e^{-1.5M} \tag{B 12}$$

$$q_{Female} \approx q_{PreRec1} \frac{CPUE_{Female}}{CPUE_{PreRec1}} \tag{B 13}$$

where q_{Leg}, $q_{PreRec1}$, and q_{Female} are catchability of legal male, prerecruit-1 male, and female crabs, respectively.

The $P_{l',l}$ was determined as follows:

Annual growth increment (x) of crab was assumed to have a normal distribution with a mean growth increment $\bar{l}$ and a standard deviation s. Then,

$$P_{l',l} = \frac{\int_{l_1 - \tau_{l'}}^{l_2 - \tau_{l'}} e^{\frac{-(x-\bar{l})^2}{2s^2}} dx}{\sum_{l=1}^{n} \int_{l_1 - \tau_{l'}}^{l_2 - \tau_{l'}} e^{\frac{-(x-\bar{l})^2}{2s^2}} dx} \quad . \tag{B 14}$$

The male molt probability, m_l, in length-class l was estimated using the logistic function, $1-\frac{1}{1+f\,e^{-d\,z}}$,

or

$$\frac{g}{g+qe^{-r(z-g)}} \quad \text{(three-parameter model for snow crab).} \qquad \text{(B 15)}$$

For Tanner and snow crabs, terminal molt at maturity of female crabs was assumed in estimating female abundance. So, the cohort decline formula at time $t+1$ was independent of size as follows:

$$N(0)_{t+1} = N(0)_t\ e^{-(M+HM_2\ \delta+BYM)} \qquad \text{(B 16)}$$

where N_t is the total number of crabs summed over all size groups at time t.

The average spawning biomass was calculated in two steps. First, the average mature abundance in numbers for a given male to female mating ratio was estimated. Second, the effective average stock biomass was calculated in proportion to this abundance. Thus, the average male stock abundance in number ($MSSN(F)$) for a given F at time t + 1 was computed using the following steps:

when $t + 1 = 1$,

$$\overline{N}(0)_{t+1} = \sum_{l'=1}^{3} N(0)_{l',t}\,(1-e^{-(M+HM_1\ \delta+BYM)})/(M+HM_1\ \delta+BYM), \qquad \text{(B 17)}$$

when $t+1 \geq 2$,

$$\overline{N}(F)_{t+1} = \sum_{l'=1}^{3} N(0)_{l',t}\,(1-e^{-(M+HM_1\ \delta+BYM)})/(M+HM_1\ \delta+BYM)+$$
$$\sum_{l'=4}^{10} N(F)_{l',t}\,(1-e^{-(M+F+BYM)})/(M+F+BYM), \text{ and} \qquad \text{(B 18)}$$

the sum of average mature male abundances, in number, over the reproductive ages was estimated by

$$MSSN(F) = \sum_{t=t_r}^{\lambda} \overline{N}(F)_{t+1} . \quad \text{(B 19)}$$

The average female stock abundance in number (*FSSN(0)*) for a zero *F* (since females are not allowed to be retained as catch) at time $t + 1$ was computed using the following formulas:

when $t + 1 = 1$,

$$\overline{N}(0)_{t+1} = \sum_{l'=1}^{2} N(0)_{l',t} (1 - e^{-(M + HM_2 \delta + BYM)}) / (M + HM_2 \delta + BYM), \quad \text{(B 20)}$$

when when $t+1 \geq 2$,

$$\overline{N}(0)_{t+1} = \sum_{l'=3}^{10} N(0)_{l',t} (1 - e^{-(M + HM_2 \delta + BYM)}) / (M + HM_2 \delta + BYM), \text{ and} \quad \text{(B 21)}$$

$$\overline{N}(0)_{t+1} = N(0)_t (1 - e^{-(M + HM_2 \delta + BYM)}) / (M + HM_2 \delta + BYM) \quad \text{(B 22)}$$

for Tanner and snow crab females.

The sum of average mature female abundance, in numbers, over the reproductive ages was estimated by

$$FSSN(0) = \sum_{t=t_r}^{\lambda} \overline{N}(0)_{t+1} . \quad \text{(B 23)}$$

Note that the prerecruit-1 and class-1 female entry age, t_r, was equivalent to the initial maturity age and t_r was arbitrarily set at 0.

The mating ratio (the number of females that a male can mate during a spawning period) was applied to adjust the average spawning stock abundances to determine effective total spawning stock biomass (*ESB(F)*) corresponding to a fishing mortality *F*.

For example, if one male mates with three females during the breeding period, the effective spawning abundance for each sex was estimated as follows:

1) If $FSSN(0) \leq MSSN(F)$, then effective male spawning abundance was set at *FSSN(0)/3,* and the corresponding female value was set at *FSSN(0)*.
2) If *FSSN(0) > MSSN(F)*, but $3\,MSSN(F)) \geq FSSN(0)$, then effective male spawning abundance was set at *FSSN(0)/3* and the corresponding female estimate was set at *FSSN(0)*.
3) If *FSSN(0) > MSSN(F)*, but *(3 MSSN(F)) < FSSN(0)*, then effective male spawning abundance was set at *MSSN(F)* and the corresponding female value was set at *3 MSSN(F)*.

The effective spawning biomass for male (*MSSB(F)*) was estimated by the following formulas:

when $t + 1 = 1$,

$$\bar{B}(0)_{t+1} = [\sum_{l'=1}^{3} N(0)_{l',t}\, W_{l'}\,(1-e^{-(M+HM_1\delta+BYM)})/(M+HM_1\delta+BYM)]\frac{effective\ MSSN(F)}{MSSN(F)},$$

(B 24)

when $t+1 \geq 2$,

$$\bar{B}(F)_{t+1} = [\sum_{l'=1}^{3} N(0)_{l',t}\, W_{l'}\,(1-e^{-(M+HM_1\delta+BYM)})/(M+HM_1\delta+BYM) + \sum_{l'=4}^{10} N(F)_{l',t}\, W_{l'}\,(1-e^{-(M+F+BYM)})/(M+F+BYM)]\frac{effective\ MSSN(F)}{MSSN(F)}$$

, and (B 25)

$$MSSB(F) = \sum_{t=t_r}^{\lambda} \bar{B}(F)_{t+1}\ .$$ (B 26)

The corresponding equations for female effective spawning biomass (*FSSB(0)*) are:
when $t + 1 = 1$,

$$\bar{B}(0)_{t+1} = [\sum_{l'=1}^{2} N(0)_{l',t}\, W_{l'}\,(1 - e^{-(M + HM_2\,\delta + BYM)})/(M + HM_2\,\delta + BYM)]\,\frac{effective\ FSSN(0)}{FSSN(0)},$$

(B 27)

when $t+1 \geq 2$,

$$\bar{B}(0)_{t+1} = [\sum_{l'=3}^{10} N(0)_{l',t}\, W_{l'}\,(1 - e^{-(M + HM_2\,\delta + BYM)})/(M + HM_2\,\delta + BYM)]\,\frac{effective\ FSSN(0)}{FSSN(0)},$$

(B 28)

$$FSSB(0) = \sum_{t=t_r}^{\lambda} \bar{B}(0)_{t+1}\quad, \tag{B 29}$$

where, following Beyer (1987),

$$W_l = (\frac{1}{z_{up} - z_{low}})(\frac{a}{b+1})(z_{up}^{b+1} - z_{low}^{b+1}),\ \text{and} \tag{B 30}$$

$$W = a\, z^{b}. \tag{B 31}$$

The combined effective total spawning stock biomass-per-recruit ($(ESB/R)_F$) was determined by $(ESB/R)_F = (MSSB(F) + FSSB(0))/R$, (B 32)

where R (number of prerecruit-1 males plus class-1 females) was fixed at 2,000.

APPENDIX C: LIST OF NOTATIONS

ADF&G = Alaska Department of Fish and Game

AFSC = Alaska Fisheries Science Center

$\overline{B}(F)_t$ and $\overline{B}(0)_t$ = average effective spawning biomasses (adjusted for male to female mating ratio) in a cohort corresponding to a fishing mortality F (for legal males) and $F = 0$ (for females or sublegal males) in year t, respectively

BRP = biological reference point, values of parameters that are used as benchmarks against which the abundance of the stock or the fishing mortality (equivalent harvest rate) can be measured to determine the stock status

BSAI = Bering Sea and Aleutian Islands

BYM = constant annual instantaneous bycatch mortality

$c(F)_t$ = sum of catches in all size groups of legal males in a cohort in number corresponding to a fishing mortality F in year t

$C(F)$ = sum of $c(F)_t$ through the fishery life span (i.e., stock catch in number), from t_r to λ

CLA = Catch Length Analysis

CPT = Crab Plan Team

CPUE = catch-per-unit-effort

CSA = Catch Survey Analysis

e = base of natural logarithms

EEZ = Exclusive Economic Zone, 3 to 200 nautical miles from the shoreline

$E(F_{MSY})$ = exploitation rate corresponding to a fishing mortality F_{MSY}

$ESB\ (F)$, $ESB\ (F_{MSY})$, and $ESB\ (0)$ = effective total (males and females) spawning stock biomasses (adjusted for male to female mating ratio) corresponding to a fishing mortality F, F_{MSY}, and $F = 0$, respectively ($ESB(F)$ is used in *S-R* relationship)

$(ESB/R)_{ESB=0}$ = effective total spawning stock biomass-per-recruit determined as the reciprocal of the slope at the origin of the *S-R* curve

$(ESB/R)_F$ and $(ESB/R)_{F=0}$ = effective total spawning stock biomass-per-recruit corresponding to a fishing mortality F and F = 0, respectively

F = constant instantaneous fishing mortality for a biological year t, a product of annual fishing mortality and actual fishing period (δ) as a fraction of an year

$F_{0.1}$ = instantaneous fishing mortality at which the tangent to the yield-per-recruit curve is one-tenth of that at F = 0

F_{OY} = optimum yield producing fishing mortality

$F_{x\%}$ = fishing mortality that produces a long-term average (equilibrium) spawner biomass-per-recruit equivalent to that of $x\%$ of the equilibrium spawner biomass-per-recruit produced at F = 0

F_{MSY} = constant instantaneous fishing mortality that will produce MSY at the MSY-producing biomass

$F(SSB)$ = total (directed and non-directed fisheries) fishing mortality as a function of SSB used in MSY and Target Control Rules definitions

FMP = Fishery Management Plan

FPA = Fishery Performance Analysis

$FSSB(0)$ = sum of average effective spawning biomass of mature female crab over an average fishery life span (i.e., effective spawning stock biomass of females) corresponding to a zero (direct) fishing mortality on females

$FSSN(0)$ = sum of average mature female crab abundances in number over an average fishery life span (i.e., mature female stock abundance) corresponding to a zero fishing mortality

GHL = guideline harvest level

h = proportion of sublegal males and females that died due to capture and release to sea (i.e., mortality due to handling of sublegal male and all female crabs)

HM_i = constant annual instantaneous handling mortality (defined as a function of F with h and sublegal catchability as parameters in Appendix B, i =1 for male, i = 2 for female)

j' = size interval index for recruit and postrecruit male crabs for catch estimation

$\bar{l}$ = mean of x

l_2 and l_1 = lower and upper limits, respectively, of a receiving length interval l for $P_{l',l}$ estimation

LBA = Length-Based Analysis

M = constant annual instantaneous natural mortality

MB_n = total (male plus female) mature biomass of the actual stock in year n

MFMT = maximum fishing mortality threshold, usually set to F_{MSY}

m_l = molting probability in a lengthclass l (estimation method using a logistic model is described in Appendix B)

MSFCMA = Magnuson-Stevens Fishery Conservation and Management Act

$MSSB(F)$ = sum of average effective spawning biomass of mature legal and sublegal male crab over an average fishery life span (i.e., effective spawning stock biomass of males) corresponding to a fishing mortality F on legal males

$MSSN(F)$ = sum of average mature legal and sublegal male crab abundances in number over an average fishery life span (i.e., mature male stock abundance) corresponding to a fishing mortality F on legal males

MSST = minimum total spawning stock biomass threshold, equivalent to the greater of (a) ½ $SSB\ (F_{MSY})$ or (b) the minimum effective spawning stock biomass size at which rebuilding to $SSB\ (F_{MSY})$ will occur within 10 years of fishing at MFMT

MSY = maximum sustainable yield, the largest long-term average yield that can be taken from a stock (or a stock complex) under prevailing ecological and environmental conditions

n = total number of length intervals available in a cohort for $P_{l',l}$ estimation

NMFS = National Marine Fisheries Service

$N(F)_{l,\,t}$ and $N(0)_{l,\,t}$ = abundances in numbers in a length-class l of a cohort corresponding to a fishing mortality F (for legal males) and F = 0 (for females or sublegal males) in year t, respectively

$\overline{N}(F)_t$ and $\overline{N}(0)_t$ = average abundances in numbers in a cohort corresponding to a fishing mortality F (for legal males) and F = 0 (for females or sublegal males) in year t, respectively

NPFMC = North Pacific Fishery Management Council

OY = optimum yield, the amount of yield that will provide the greatest overall benefit to the nation, particularly with respect to food production and recreational opportunities and taking into account the protection of marine ecosystems, it may be less than MSY

$P_{l',l}$ = probability of crabs in a length group *l'* growing into a length group *l* (estimation method using a normal probability model is described in Appendix B)

$R(F)$, $R(F_{MSY})$, and $R(0)$ = numbers of recruits to male prerecruit 1 and female class1 size groups produced by $ESB(F)$, $ESB(F_{MSY})$, and $ESB(0)$, respectively

R_{max} = asymptotic (maximum) recruitment, set to 2000 for per-recruit analysis

s = standard deviation of x

SFA = Sustainable Fisheries Act

SDC = Status Determination Criteria

S-R = spawner-recruit

$SSB(F)$, $SSB(F_{MSY})$, and $SSB(0)$ = nominal (unadjusted for male to female mating ratio) total mature stock biomass estimated from 2000 recruits corresponding to a fishing mortality F, F_{MSY}, and $F = 0$ on legal males, respectively ($ESB(F) \leq SSB(F)$)

SY_n = sustainable yield from the actual stock in year n

T = average time elapsed between the mid-survey date (stock enumeration date; i.e., start of a biological year) and start date of a fishing period as a fraction of a year

T_{max} = maximum time period required to rebuild a stock with the MFMT level of fishing mortality to the MSY producing level

T_{min} = minimum time period required to rebuild a stock with zero level of F to the MSY producing level

t_r = relative age at recruitment in year

VBA = Visual Basic for Applications

$W(F_{MSY})$ and $W(0)$ = mean weights of individuals in the MSY-producing biomass and virgin biomass, respectively

W_l = mean weight of crabs in a length-class l,

x = a normal random variable representing the annual growth increment,

$X = ESB(F_{MSY})/ESB(0)$ ratio

$y(F)_t$ = sum of catches in all size groups of legal males in a cohort in weight corresponding to a fishing mortality F and year t

$Y(F)$ = sum of $y(F)_t$ through the fishery life span (i.e., stock catch in weight), from t_r to λ

z = mid-carapace length (CL) or mid-carapace width (CW) of a size interval in the molt probability model

$Z_{MSY} = F_{MSY} + M$, constant instantaneous total mortality

z_{up} and z_{low} = upper and lower size limits, respectively, of a length-class l for mean weight at size calculation

λ = relative maximum age of a cohort in year

δ = duration of average fishing period as a fraction of a year (handling and fishing mortality occur during this time period, hence *HM* and annual fishing mortality values are scaled to this period)

τ = a parameter estimated from a spawning biomass-per-recruit ratio, which influences the steepness near the origin and overall shape of the *S-R* curve, referred to as the *S-R* shape parameter in this paper (but Mace (1994) named it as the extinction parameter)

$\tau_{l'}$ = mid length of a providing length interval l' for $P_{l',l}$ estimation

$\alpha, \beta, \gamma,$ and θ = parameters in the *S-R* models

d, f, g, q and r = parameters in the logistic molting probability model

a and b = parameters in the weight-length model

Table 6.1. Instantaneous natural mortality (M), instantaneous bycatch mortality (BYM), handling mortality rate (h), average fishing time (δ), and the lapsed time between the survey midpoint and start of the fishing periods (T) used for identifying threshold biological reference points for seven BSAI crab stocks.

Species	M	BYM	h	δ (year)	T (year)
Bristol Bay red king crab	0.3	0.01	0.20	0.0121	0.3836
Bering Sea snow crab	0.4	0.01	0.25	0.1279	0.5342
Bering Sea Tanner crab	0.4	0.02	0.20	0.0425	0.3315
St. Matthew blue king crab	0.3	0.02	0.20	0.0212	0.2603
Pribilof blue king crab	0.3	0.02	0.20	0.0308	0.1890
Western Aleutian Islands golden king crab	0.3	0.01	0.20	0.9490	0.0575
Eastern Aleutian Islands golden king crab	0.3	0.01	0.20	0.1973	0.0575

Table 6.2a. Bristol Bay red king crab parameter values used in the BRP simulations. CV = coefficient of variation, CL = carapace length in mm.

Parameter	Male	Female	Remarks
Growth Increment Model (equation B 14)			
$\bar{l}$	16.0 CL[1]	4.0 CL[2]	[1]Weber and Miyahara (1962), [2]Gray (1963)
s	2.4 CL	0.6 CL	s estimated assuming 15% CV
Molt Probability Model (equation B 15)			
f	295159.6		Medium growth period (1985-1991); Zheng et al. (1995b)
d	0.089		
Molt Probability		1.0	Zheng et al. (1995a)
Weight-Length Model (g–mmCL) (equation B 30)			
a	0.0003614[3]	0.02286[4]	[3]Balsiger (1974), [4]Zheng et al. (1995a)
b	3.16	2.234	

Table 6.2b. Estimates of maximum sustainable yield (MSY)-producing total mature biomass as a proportion of virgin total mature biomass ($SSB(F_{MSY})/SSB(0)$) and MSY-producing harvest rate ($E(F_{MSY})$) of legal males for Beverton and Holt (Beverton and Holt 1957) and Ricker (Ricker 1954) stock-recruitment (*S-R*) models for Bristol Bay red king crab. M = annual instantaneous natural mortality, h = handling mortality rate, BYM = annual instantaneous bycatch mortality, mating ratio = number of females mated by one male in one spawning occasion, and τ= extinction parameter defining the steepness near the origin and shape of the *S-R* curve. Suggested precautionary threshold values are marked in bold.

Input Parameter Range			Estimated Biological Reference Points				
	Mating			Beverton and Holt *S-R*		Ricker *S-R*	
Mortality	Ratio	τ		Range	Median	Range	Median
M = 0.2, 0.3,0.4 h = 0, 0.2, BYM = 0, 0.01	1:1,1:2, 1:3	0.05-0.75	$SSB(F_{MSY})/SSB(0)$ $E(F_{MSY})$	0.37-0.90 0.04-1.00	0.53 0.46	0.27-0.89 0.05-1.00	0.51 0.59
M = 0.2, 0.3, 0.4 h = 0.2, BYM = 0.01	1:1,1:2, 1:3	0.3-0.5	$SSB(F_{MSY})/SSB(0)$ $E(F_{MSY})$	0.46-0.75 0.11-0.77	0.54 0.39	0.40-0.73 0.13-0.97	0.51 0.47
M = 0.3 h = 0.2, BYM = 0.01	1:1,1:2, 1:3	0.3-0.5	$SSB(F_{MSY})/SSB(0)$ $E(F_{MSY})$	0.46-0.74 0.16-0.60	**0.54** **0.43**	0.40-0.73 0.17-0.79	**0.50** **0.50**
M = 0.3 h = 0.2, BYM = 0.01	1:1	0.3-0.5	$SSB(F_{MSY})/SSB(0)$ $E(F_{MSY})$	0.63-0.74 0.16-0.28	0.69 0.21	0.58-0.73 0.17-0.35	0.66 0.24
M = 0.3 h = 0.2, BYM = 0.01	1:3	0.3-0.5	$SSB(F_{MSY})/SSB(0)$ $E(F_{MSY})$	0.46-0.55 0.40-0.60	0.50 0.50	0.40-0.52 0.46-0.79	0.46 0.60
$M(male)$ = 0.3, $M(female)$ = 0.47 h = 0.2, BYM = 0.01	1:1	0.3-0.5	$SSB(F_{MSY})/SSB(0)$ $E(F_{MSY})$	0.63-0.74 0.16-0.28	0.69 0.21	0.58-0.73 0.17-0.35	0.66 0.24
$M(male)$ = 0.3, $M(female)$ = 0.47 h = 0.2, BYM = 0.01	1:3	0.3-0.5	$SSB(F_{MSY})/SSB(0)$ $E(F_{MSY})$	0.46-0.55 0.40-0.60	0.50 0.50	0.40-0.52 0.46-0.79	0.46 0.60

Table 6.3a. Bering Sea snow crab parameter values used in the BRP simulations. CV = coefficient of variation, CW = carapace width in mm.

Parameter	Male	Female	Remarks
Growth Increment Model (equation B 14)			
$\bar{l}$	18.0 CW		Zheng (2001)
s	2.7 CW		*s* estimated assuming 15% CV
Three Parameter Molt Probability Model (equation B 15)			
g,	77.876411		Somerton (1981)
q	67.85		
r	0.05415		
Molt Probability		0	
Weight-Length Model (g-mmCW) (equation B 30)			
a	0.00023	0.00253	Somerton (1981)
b	3.12948	2.56427	

Table 6.3b. Estimates of maximum sustainable yield (MSY)-producing total mature biomass as a proportion of virgin total mature biomass ($SSB(F_{MSY})/SSB(0)$) and MSY-producing harvest rate ($E(F_{MSY})$) of legal males for Beverton and Holt (Beverton and Holt 1957) and Ricker (1954) stock-recruitment (*S-R*) models for Bering Sea snow crab. *M* = annual instantaneous natural mortality, *h* = handling mortality rate, *BYM* = annual instantaneous bycatch mortality, mating ratio = number of females mated by one male in one spawning occasion, and τ= extinction parameter defining the steepness near the origin and shape of the *S-R* curve. Suggested precautionary threshold values are marked in bold.

Input Parameter Range			Estimated Biological Reference Points				
	Mating			Beverton and Holt *S-R*		Ricker *S-R*	
Mortality	Ratio	τ		Range	Median	Range	Median
M = 0.3, 0.35,0.4	1:1,1:2,	0.05-0.75	$SSB(F_{MSY})/SSB(0)$	0.38-0.89	0.62	0.31-0.89	0.58
h = 0, 0.25, *BYM* = 0, 0.01	1:3		$E(F_{MSY})$	0.06-1.0	0.39	0.06-1.0	0.47
M = 0.3, 0.35, 0.4	1:1,1:2,	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.5-0.75	0.63	0.45-0.73	0.59
h = 0.25, *BYM*=0.01	1:3		$E(F_{MSY})$	0.15-0.58	0.32	0.17-0.73	0.39
M = 0.4	1:1,1:2,	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.53-0.75	**0.63**	0.47-0.73	**0.59**
h = 0.25, *BYM* = 0.01	1:3		$E(F_{MSY})$	0.20-0.58	**0.36**	0.22-0.73	**0.44**
M = 0.4	1:1	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.63-0.75	0.69	0.59-0.73	0.66
h = 0.25, *BYM* = 0.01			$E(F_{MSY})$	0.20-0.36	0.27	0.22-0.45	0.32
M = 0.4	1:3	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.53-0.62	0.57	0.47-0.59	0.53
h = 0.25, *BYM* = 0.01			$E(F_{MSY})$	0.39-0.58	0.48	0.44-0.73	0.57

Table 6.4a. Bering Sea Tanner crab parameter values used in the BRP simulations. CW = carapace width in mm.

Parameter	Male	Female	Remarks
Growth Increment Model (equation B 14)			
$\bar{l}$	25.2 CW		Donaldson et al. (1980, 1981)
s	2.8 CW		
Molt Probability Model (equation B 15)			
f	108632.7		Applicable for an average molting period, Zheng et al. (1998)
d	0.085		
Molt Probability		0	
Weight-Length Model (g-mmCW) (equation B.30)			
a	0.00019	0.00182	Somerton (1981)
b	3.09894	2.70462	

Table 6.4b. Estimates of maximum sustainable yield (MSY)-producing total mature biomass as a proportion of virgin total mature biomass ($SSB(F_{MSY})/SSB(0)$) and MSY-producing harvest rate ($E(F_{MSY})$) of legal males for Beverton and Holt (Beverton and Holt 1957) and Ricker (Ricker 1954) stock-recruitment (*S-R*) models for Bering Sea Tanner crab. M = annual instantaneous natural mortality, h = handling mortality rate, BYM = annual instantaneous bycatch mortality, mating ratio = number of females mated by one male in one spawning occasion, and τ = extinction parameter defining the steepness near the origin and shape of the *S-R* curve. Suggested precautionary threshold values are marked in bold.

Input Parameter Range			Estimated Biological Reference Points				
Mortality	Mating Ratio	τ		Beverton and Holt *S-R* Range	Beverton and Holt *S-R* Median	Ricker *S-R* Range	Ricker *S-R* Median
M = 0.3, 0.35,0.4	1:1,1:2,	0.05-0.75	$SSB(F_{MSY})/SSB(0)$	0.45-0.91	0.62	0.43-0.9	0.59
h = 0, 0.2, BYM = 0, 0.02	1:3		$E(F_{MSY})$	0.06-0.99	0.54	0.06-1.0	0.66
M = 0.3, 0.35, 0.4	1:1,1:2,	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.52-0.77	0.65	0.47-0.75	0.61
h = 0.2, BYM=0.02	1:3		$E(F_{MSY})$	0.17-0.88	0.40	0.19-0.98	0.50
M = 0.4	1:1,1:2,	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.54-0.77	**0.66**	0.51-0.75	**0.62**
h = 0.2, BYM = 0.02	1:3		$E(F_{MSY})$	0.23-0.88	**0.46**	0.26-0.98	**0.57**
M = 0.4	1:1	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.66-0.77	0.71	0.62-0.75	0.69
h = 0.2, BYM = 0.02			$E(F_{MSY})$	0.23-0.46	0.33	0.26-0.57	0.38
M = 0.4	1:3	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.54-0.55	0.54	0.51-0.54	0.54
h = 0.2, BYM = 0.02			$E(F_{MSY})$	0.84-0.88	0.88	0.88-0.98	0.88

Table 6.5a. St. Matthew Island blue king crab parameter values used in the BRP simulations. CL: carapace length in mm.

Parameter	Male	Female	Remarks
Growth Increment Model (equation B 14)			
$\bar{l}$	14.1 CL[1]	4.0 CL[2]	[1]Otto and Cummiskey (1990) [2]Red king crab values
s	3.1 CL	0.6 CL	
Molt Probability Model (equation B 15)			
f	0.000003		Otto and Cummiskey (1990)
d	-0.103		
Molt Probability		1	
Weight-Length Model (g-mmCL) (equation B 30)			
a	0.000329	0.02065	(R. Otto, pers. comm., NMFS Kodiak)
b	3.175	2.27	

Table 6.5b. Estimates of maximum sustainable yield (MSY)-producing total mature biomass as a proportion of virgin total mature biomass ($SSB(F_{MSY})/SSB(0)$) and MSY-producing harvest rate ($E(F_{MSY})$) of legal males for Beverton and Holt (Beverton and Holt 1957) and Ricker (Ricker 1954) stock-recruitment (*S-R*) models for St. Matthew Island blue king crab. M = annual instantaneous natural mortality, h = handling mortality rate, BYM = annual instantaneous bycatch mortality, mating ratio = number of females mated by one male in one spawning occasion, and τ = extinction parameter defining the steepness near the origin and shape of the *S-R* curve. Suggested precautionary threshold values are marked in bold.

Input Parameter Range			Estimated Biological Reference Points				
				Beverton and Holt *S-R*		Ricker *S-R*	
Mortality	Mating Ratio	τ		Range	Median	Range	Median
M = 0.2, 0.3, 0.4	1:1,1:2,	0.05-0.75	$SSB(F_{MSY})/SSB(0)$	0.38-0.78	0.52	0.27-0.78	0.50
h = 0, 0.2, BYM = 0, 0.02	1:3		$E(F_{MSY})$	0.10-1.00	0.59	0.10-1.00	0.78
M = 0.2, 0.3, 0.4	1:1,1:2,	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.48-0.62	0.54	0.42-0.59	0.50
h = 0.2, BYM=0.02	1:3		$E(F_{MSY})$	0.24-0.69	0.41	0.27-0.88	0.51
M = 0.3	1:1,1:2,	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.49-0.60	**0.54**	0.43-0.58	**0.50**
h = 0.2,BYM = 0.02	1:3		$E(F_{MSY})$	0.32-0.54	**0.43**	0.35-0.70	**0.51**
M = 0.3	1:1	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.50-0.60	0.55	0.45-0.58	0.52
h = 0.2,BYM = 0.02			$E(F_{MSY})$	0.32-0.50	0.40	0.35-0.65	0.48
M = 0.3	1:3	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.49-0.58	0.53	0.43-0.55	0.49
h = 0.2,BYM =0.02			$E(F_{MSY})$	0.35-0.54	0.44	0.40-0.70	0.53

Table 6.6a. Pribilof Islands blue king crab parameter values used in the BRP simulations. CL = carapace length in mm.

Parameter	Male	Female	Remarks
Growth Increment Model (equation B 14)			
$\bar{l}$	14.1 CL[1]	4 CL[2]	[1]Otto and Cummiskey (1990) [2]Red king crab values
s	3.1 CL	0.6 CL	
Molt Probability Model (equation B 15)			
f	0.000002		Otto and Cummiskey (1990)
d	-0.091		
Molt Probability		1	
Weight-Length Model (g-mmCL) (equation B 30)			
a	0.00047	0.02065	(R. Otto, pers. comm., NMFS Kodiak)
b	3.103	2.27	

Table 6.6b. Estimates of maximum sustainable yield (MSY)-producing total mature biomass as a proportion of virgin total mature biomass ($SSB(F_{MSY})/SSB(0)$) and MSY-producing harvest rate ($E(F_{MSY})$) of legal males for Beverton and Holt (Beverton and Holt 1957) and Ricker (Ricker 1954) stock-recruitment (*S-R*) models for Pribilof Islands blue king crab. M = annual instantaneous natural mortality, h = handling mortality rate, BYM = annual instantaneous bycatch mortality, mating ratio = number of females mated by one male in one spawning occasion, and τ = extinction parameter defining the steepness near the origin and shape of the *S-R* curve. Suggested precautionary threshold values are marked in bold.

Input Parameter Range			Estimated Biological Reference Points				
	Mating			Beverton and Holt *S-R*		Ricker *S-R*	
Mortality	Ratio	τ		Range	Median	Range	Median
M = 0.2, 0.3, 0.4	1:1,1:2,	0.05-0.75	$SSB(F_{MSY})/SSB(0)$	0.37-0.77	0.51	0.27-0.77	0.49
h = 0, 0.2, BYM = 0, 0.02	1:3		$E(F_{MSY})$	0.10-1.00	0.61	0.10-1.00	0.75
M = 0.2, 0.3, 0.4	1:1,1:2,	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.47-0.60	0.53	0.42-0.59	0.50
h = 0.2, BYM=0.02	1:3		$E(F_{MSY})$	0.25-0.71	0.42	0.27-0.87	0.50
M = 0.3	1:1,1:2,	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.47-0.59	**0.53**	0.43-0.57	**0.50**
h = 0.2, BYM = 0.02	1:3		$E(F_{MSY})$	0.32-0.56	**0.44**	0.35-0.68	**0.50**
M = 0.3	1:1	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.49-0.59	0.54	0.45-0.57	0.51
h = 0.2, BYM = 0.02			$E(F_{MSY})$	0.32-0.52	0.41	0.35-0.64	0.47
M = 0.3	1:3	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.47-0.57	0.52	0.43-0.55	0.49
h = 0.2, BYM = 0.02			$E(F_{MSY})$	0.36-0.56	0.45	0.39-0.68	0.52

Table 6.7a. Western and Eastern Aleutian Islands golden king crab parameter values used in the BRP simulations. CV: coefficient of variation, CL = carapace length in mm.

Parameter	Male	Female	Remarks
Growth Increment Model (equation B14)			
$\bar{l}$	14.5 CL[1]	4 CL[2]	[1]Watson et al. (2001) and s estimated for 15% CV, [2]Red king crab values
s	2.2 CL[1]	0.6 CL[2]	
Molt Probability Model (equation B 15)			
f			0.823 for prerecruit-1 males and 0.353 for recruits and postrecruits assumed (Doug Pengilly, pers. comm., ADF&G, Kodiak)
d			
Molt Probability		1	
Weight-Length Model (g-mmCL) (equation B 30)			
a	0.0002988 (n=276, $R^2_{adj.}$=0.93)	0.001424 (n=480, $R^2_{adj.}$=0.82)	Estimated from weight-length data for Aleutian Islands (Peter van Tamelen, pers. comm., ADF&G, Douglas)
b	3.135	2.781	

Table 6.7b. Estimates of maximum sustainable yield (MSY)-producing total mature biomass as a proportion of virgin total mature biomass ($SSB(F_{MSY})/SSB(0)$) and MSY-producing harvest rate ($E(F_{MSY})$) of legal males for Beverton and Holt (Beverton and Holt 1957) and Ricker (Ricker 1954) stock-recruitment (*S-R*) models for Western Aleutian Islands golden king crab. M = annual instantaneous natural mortality, h = handling mortality rate, BYM = annual instantaneous bycatch mortality, mating ratio = number of females mated by one male in one spawning occasion, and τ= extinction parameter defining the steepness near the origin and shape of the *S-R* curve. Suggested precautionary threshold values are marked in bold.

Input Parameter Range			Estimated Biological Reference Points				
	Mating			Beverton and Holt *S-R*		Ricker *S-R*	
Mortality	Ratio	τ		Range	Median	Range	Median
M = 0.2, 0.3, 0.4	1:1,1:2,	0.05-0.75	$SSB(F_{MSY})/SSB(0)$	0.33-0.91	0.57	0.33-0.90	0.54
h = 0, 0.2, BYM = 0, 0.01	1:3		$E(F_{MSY})$	0.04-0.98	0.51	0.04-0.98	0.68
M = 0.2, 0.3, 0.4	1:1,1:2,	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.39-0.77	0.56	0.33-0.75	0.52
h = 0.2, BYM=0.01	1:3		$E(F_{MSY})$	0.11-0.97	0.41	0.13-0.98	0.48
M = 0.3	1:1,1:2,	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.39-0.77	**0.56**	0.39-0.75	**0.52**
h = 0.2, BYM =0.01	1:3		$E(F_{MSY})$	0.14-0.97	**0.43**	0.16-0.97	**0.52**
M = 0.3	1:1	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.65-0.77	0.71	0.61-0.75	0.68
h = 0.2, BYM =0.01			$E(F_{MSY})$	0.14-0.27	0.20	0.16-0.34	0.23
M = 0.3,	1:3	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.39-0.57	0.53	0.39-0.55	0.39
h = 0.2, BYM = .01			$E(F_{MSY})$	0.41-0.97	0.51	0.47-0.97	0.97

Table 6.8. Estimates of maximum sustainable yield (MSY)-producing total mature biomass as a proportion of virgin total mature biomass ($SSB(F_{MSY})/SSB(0)$) and MSY-producing harvest rate ($E(F_{MSY})$) of legal males for Beverton and Holt (Beverton and Holt 1957) and Ricker (Ricker 1954) stock-recruitment (*S-R*) models for Eastern Aleutian Islands golden king crab. *M* = annual instantaneous natural mortality, *h* = handling mortality rate, *BYM* = annual instantaneous bycatch mortality, mating ratio = number of females mated by one male in one spawning occasion, and τ = extinction parameter defining the steepness near the origin and shape of the *S-R* curve. Suggested precautionary threshold values are marked in bold.

Input Parameter Range			Estimated Biological Reference Points				
	Mating			Beverton and Holt *S-R*		Ricker *S-R*	
Mortality	Ratio	τ		Range	Median	Range	Median
M = 0.2, 0.3, 0.4	1:1,1:2,	0.05-0.75	$SSB(F_{MSY})/SSB(0)$	0.39-0.91	0.58	0.33-0.90	0.55
h = 0, 0.2, *BYM* = 0, 0.01	1:3		$E(F_{MSY})$	0.05-0.99	0.54	0.05-1.00	0.67
M = 0.2, 0.3, 0.4	1:1,1:2,	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.45-0.77	0.57	0.39-0.75	0.53
h = 0.2, *BYM*=0.01	1:3		$E(F_{MSY})$	0.12-0.99	0.43	0.14-0.99	0.51
M = 0.3	1:1,1:2,	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.49-0.77	**0.57**	0.39-0.75	**0.53**
h = 0.2, *BYM* = 0.01	1:3		$E(F_{MSY})$	0.16-0.66	**0.47**	0.18-0.99	**0.55**
M = 0.3	1:1	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.65-0.77	0.71	0.61-0.75	0.69
h = 0.2, *BYM* = 0.01			$E(F_{MSY})$	0.16-0.30	0.22	0.18-0.37	0.25
M = 0.3	1:3	0.3-0.5	$SSB(F_{MSY})/SSB(0)$	0.49-0.58	0.54	0.39-0.55	0.49
h = 0.2, *BYM* = 0.01			$E(F_{MSY})$	0.44-0.66	0.55	0.50-0.99	0.67

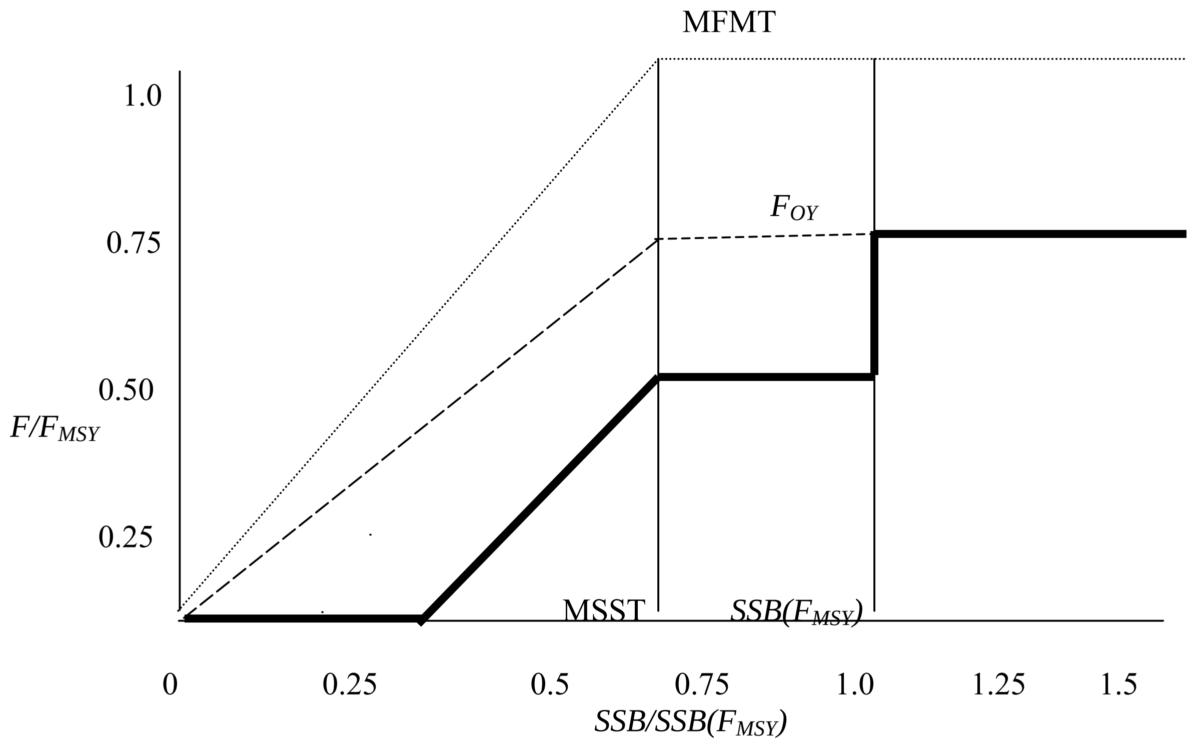

Figure 1. Default MSY control rule (dotted line), target control rule (dashed line), and rebuilding plan (solid line) for a severely depleted stock according to equations (2), (3), and (4), respectively.

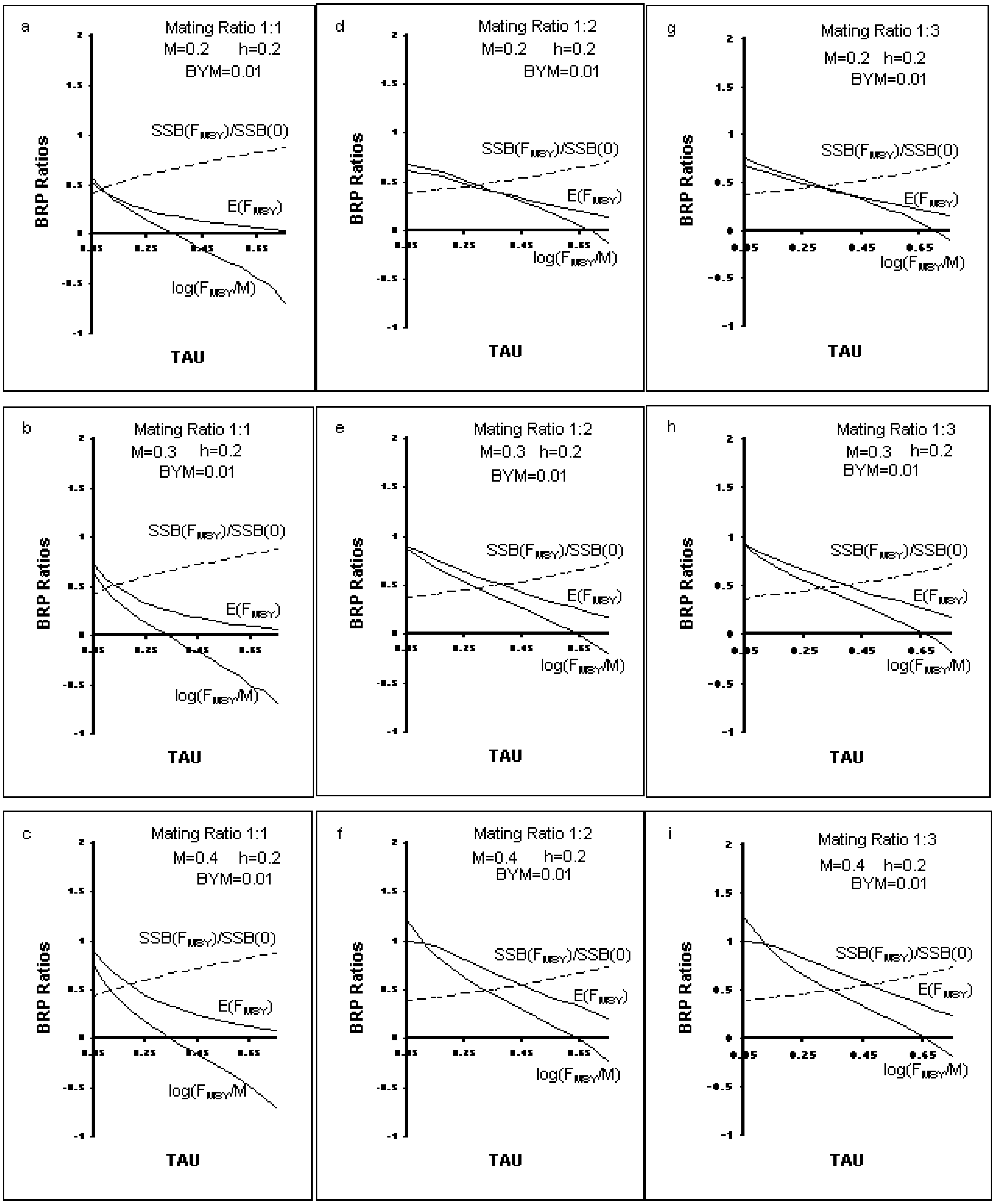

Figure 2. BRP ratios vs. Tau (τ) plots for Bristol Bay red king crab under Beverton and Holt (1957) stock-recruitment (*S*-*R*) relationship. τ = extinction parameter defining the shape of the *S*-*R* curve.

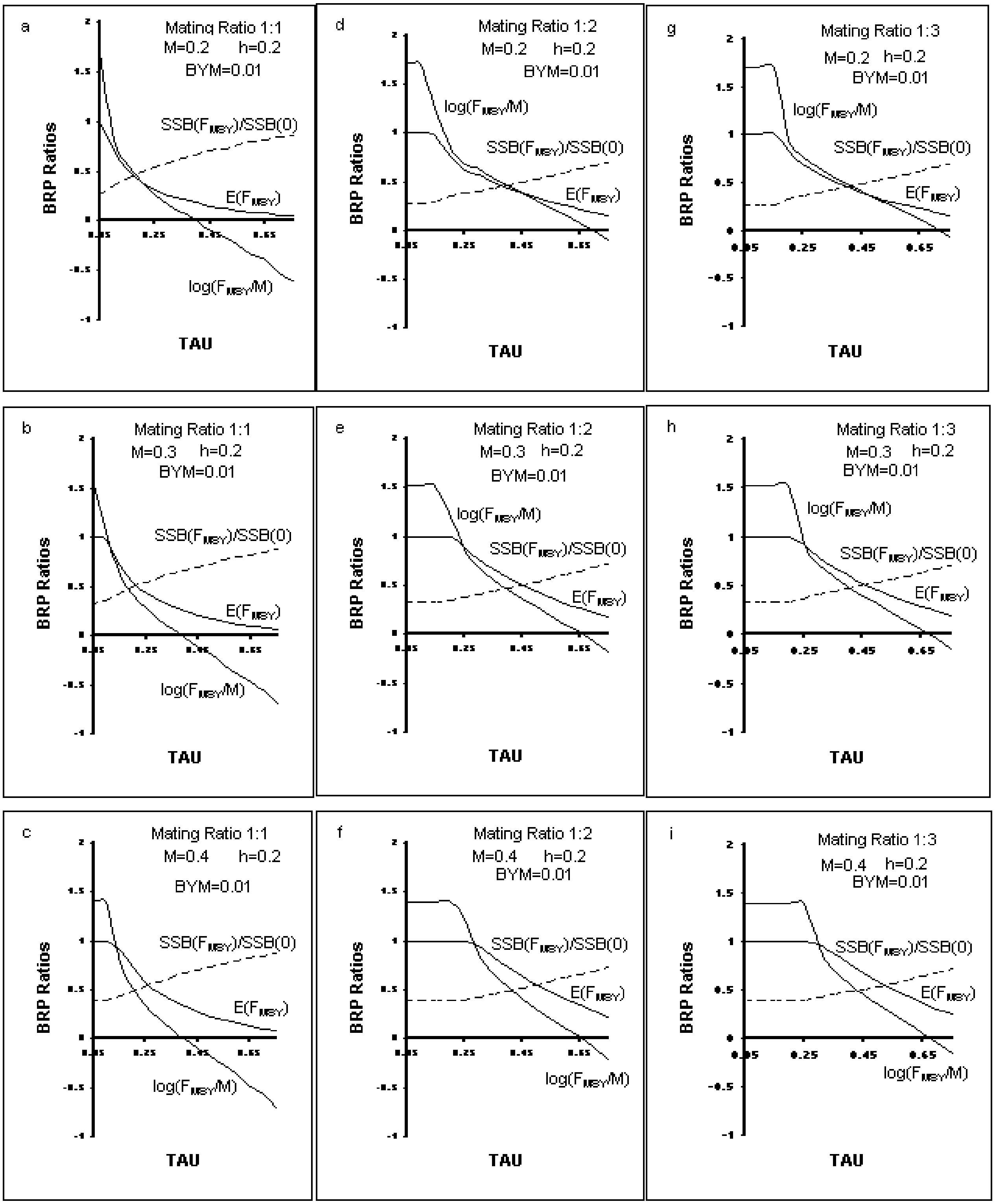

Figure 3. BRP ratios vs. Tau (τ) plots for Bristol Bay red king crab under Ricker (1954) stock-recruitment (*S*-*R*) relationship. τ = extinction parameter defining the shape of the *S*-*R* curve.

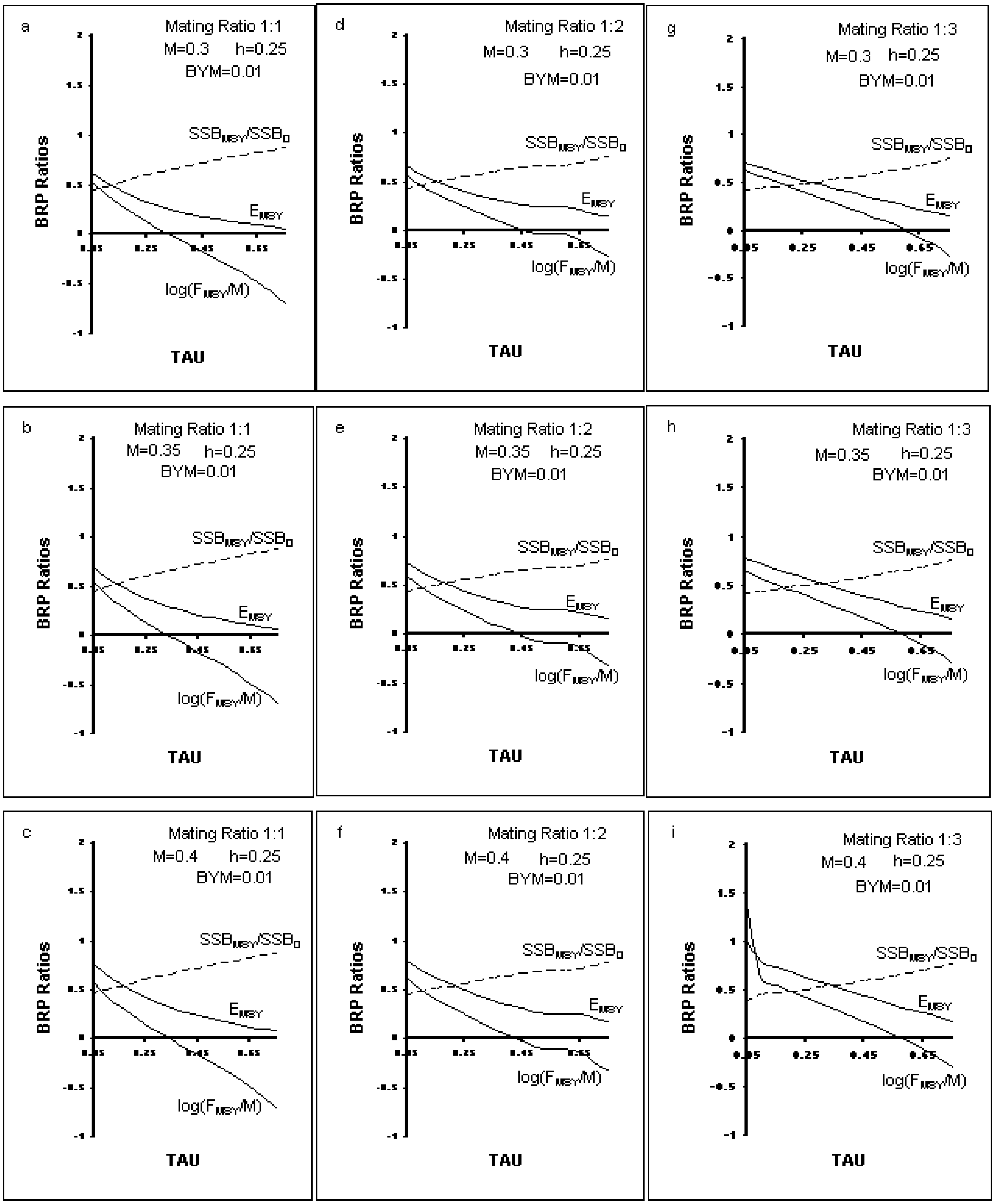

Figure 4. BRP ratios vs. Tau (τ) plots for Bering Sea snow crab under Beverton and Holt (1957) stock-recruitment (*S-R*) relationship. τ= extinction parameter defining the shape of the *S-R* curve.

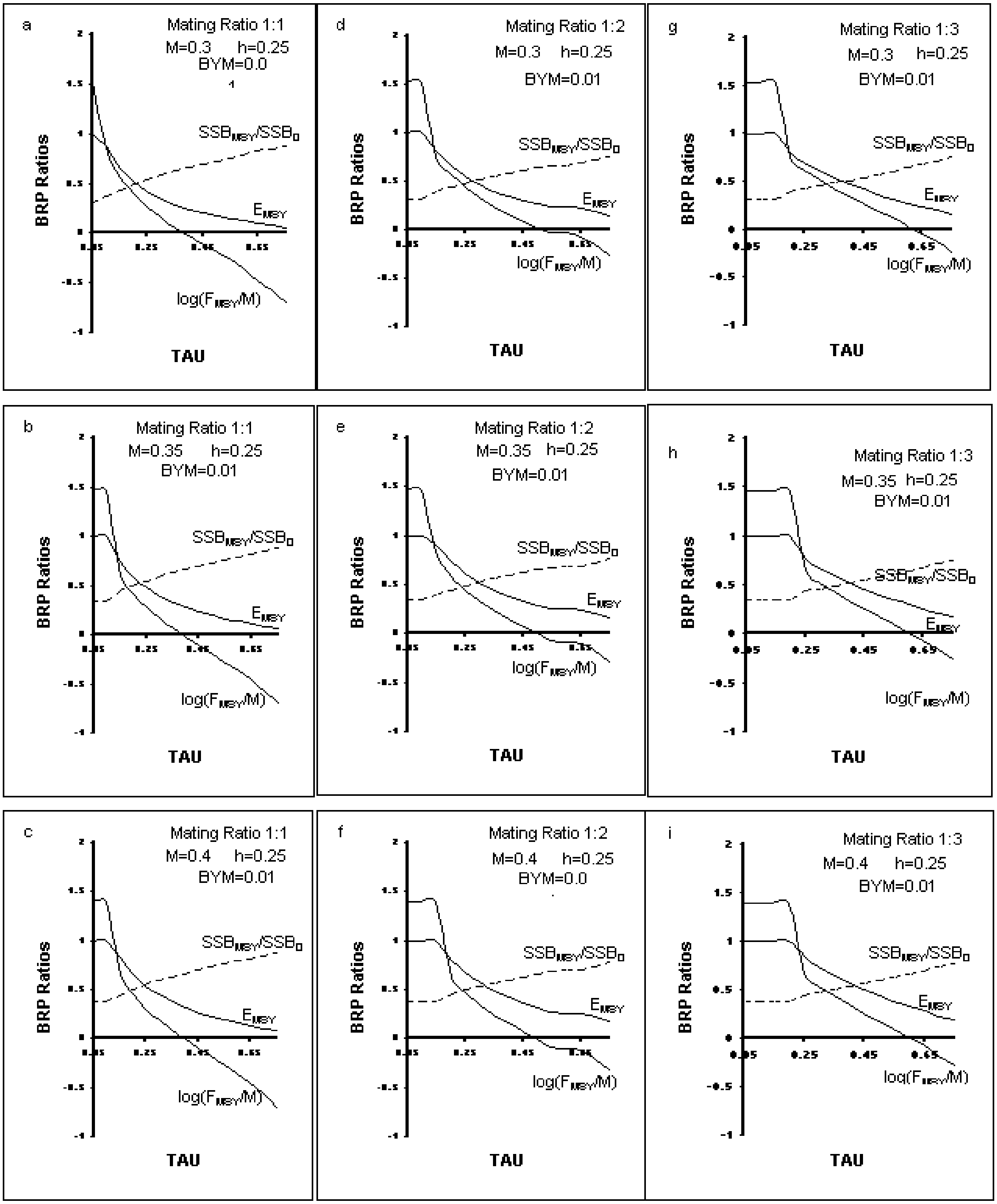

Figure 5. BRP ratios vs. Tau (τ) plots for Bering Sea snow crab under Ricker (1954) stock-recruitment (*S*-*R*) relationship. τ = extinction parameter defining the shape of the *S*-*R* curve.

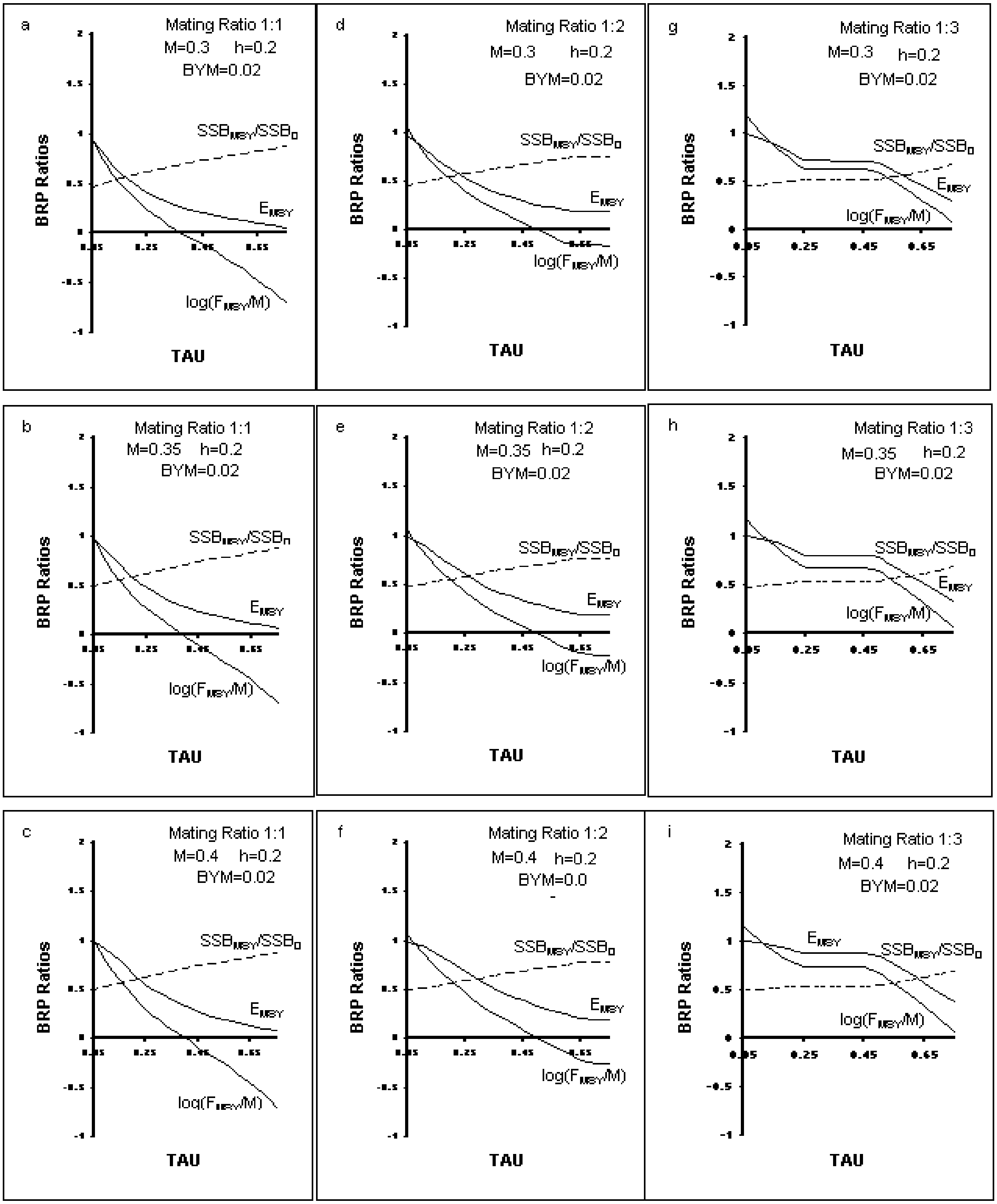

Figure 6. BRP ratios vs. Tau (τ) plots for Bering Sea Tanner crab under Beverton and Holt (1957) stock-recruitment (*S-R*) relationship. τ = extinction parameter defining the shape of the *S-R* curve.

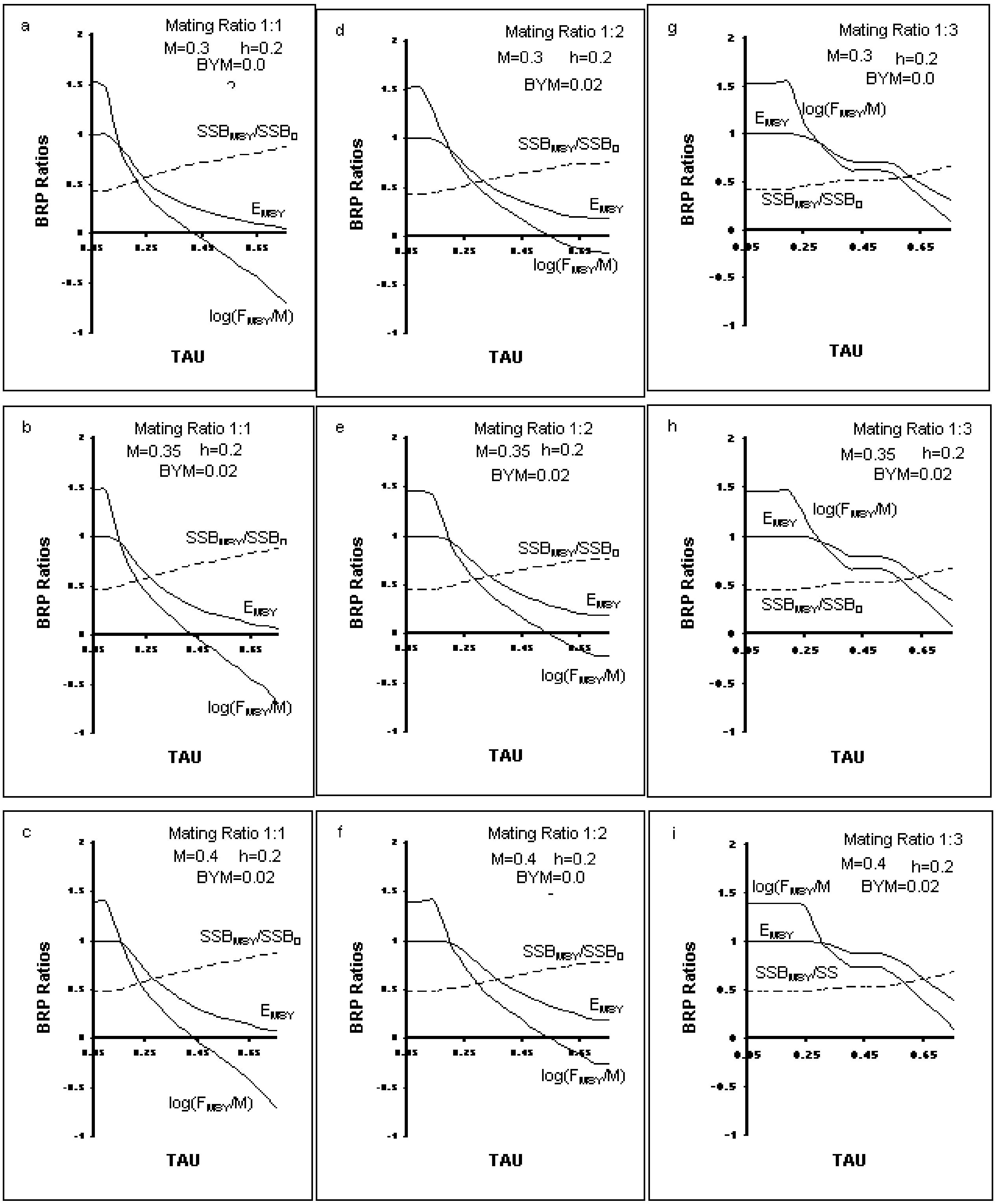

Figure 7. BRP ratios vs. Tau (τ) plots for Bering Sea Tanner crab under Ricker (1954) stock-recruitment (*S*-*R*) relationship. τ = extinction parameter defining the shape of the *S*-*R* curve.

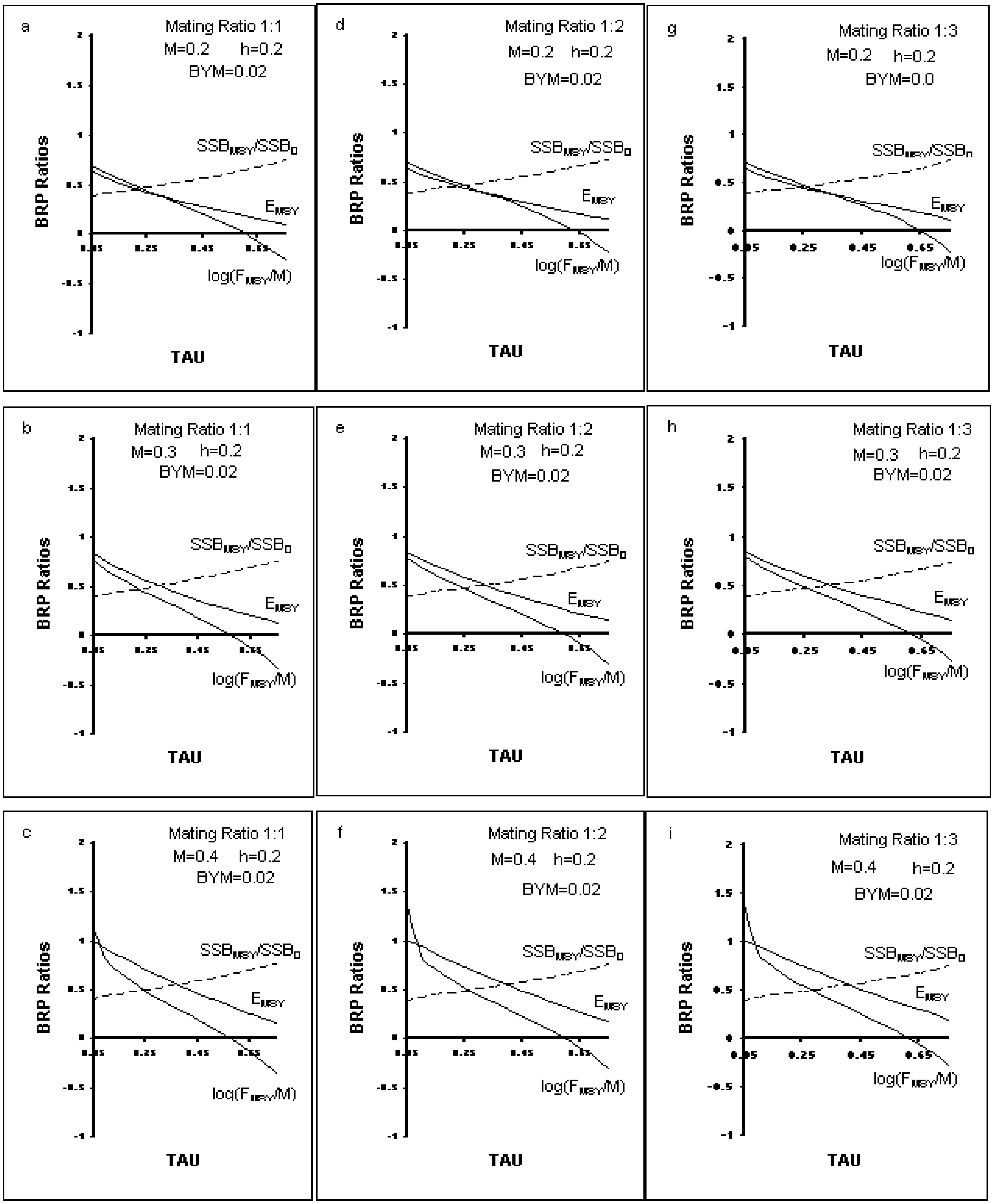

Figure 8. BRP ratios vs. Tau (τ) plots for St. Matthew Island blue king crab under Beverton and Holt (1957) stock-recruitment (*S*-*R*) relationship. τ = extinction parameter defining the shape of the *S*-*R* curve.

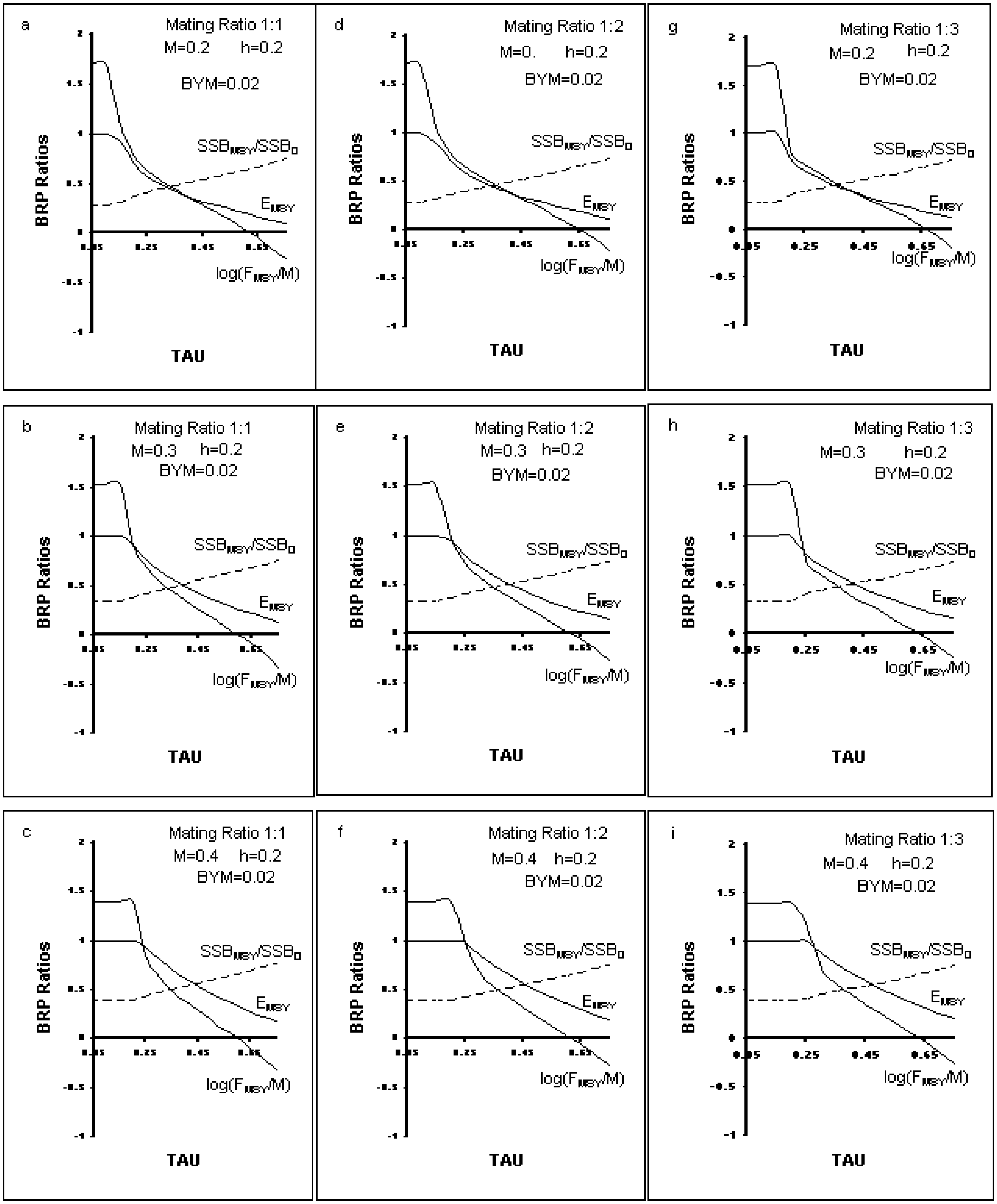

Figure 9. BRP ratios vs. Tau (τ) plots for St. Matthew Island blue king crab under Ricker (1954) stock-recruitment (*S-R*) relationship. τ = extinction parameter defining the shape of the *S-R* curve.

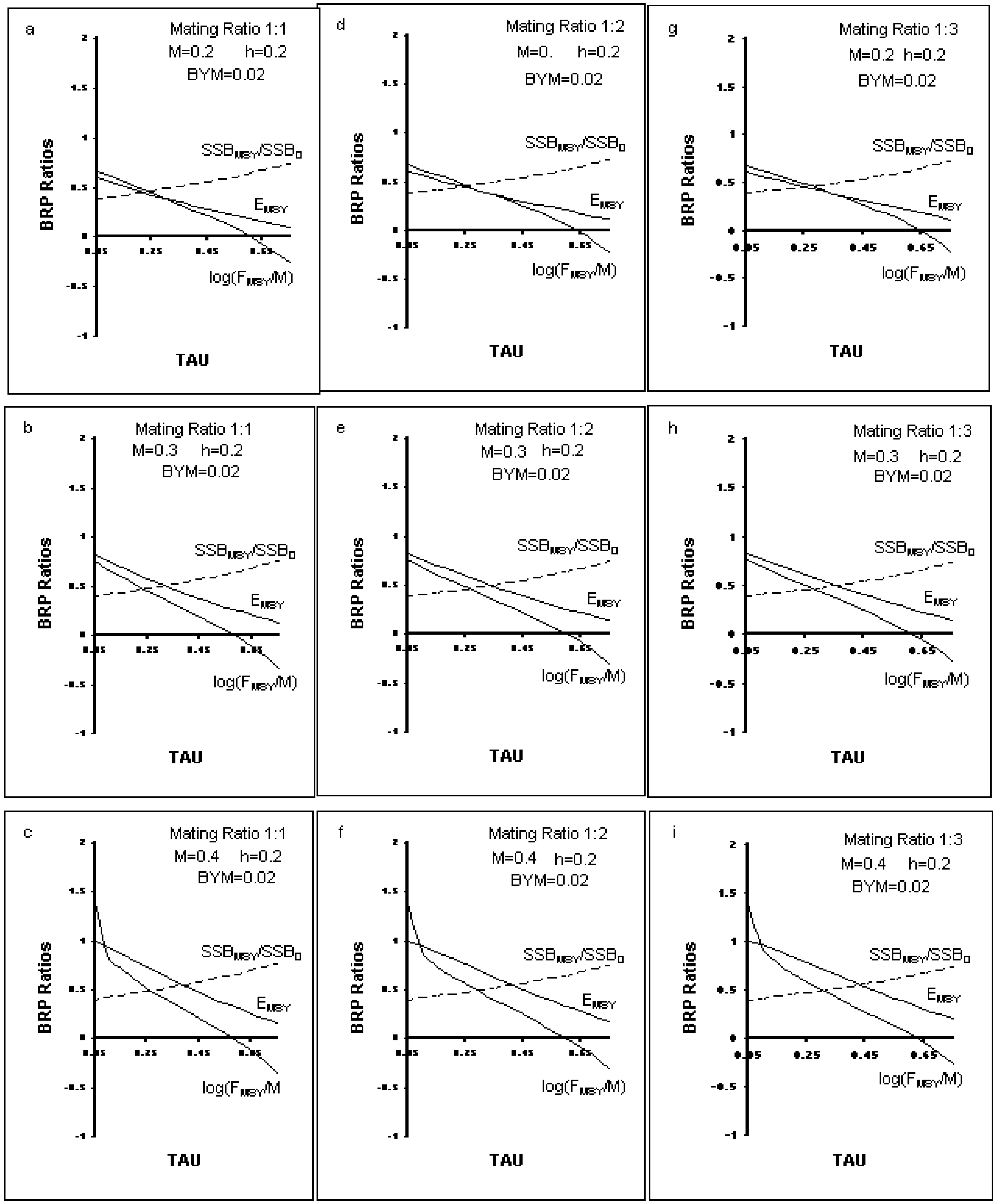

Figure 10. BRP ratio vs. Tau (τ) plots for Pribilof Islands blue king crab under Beverton and Holt (1957) stock-recruitment (*S-R*) relationship. τ = extinction parameter defining the shape of the *S-R* curve.

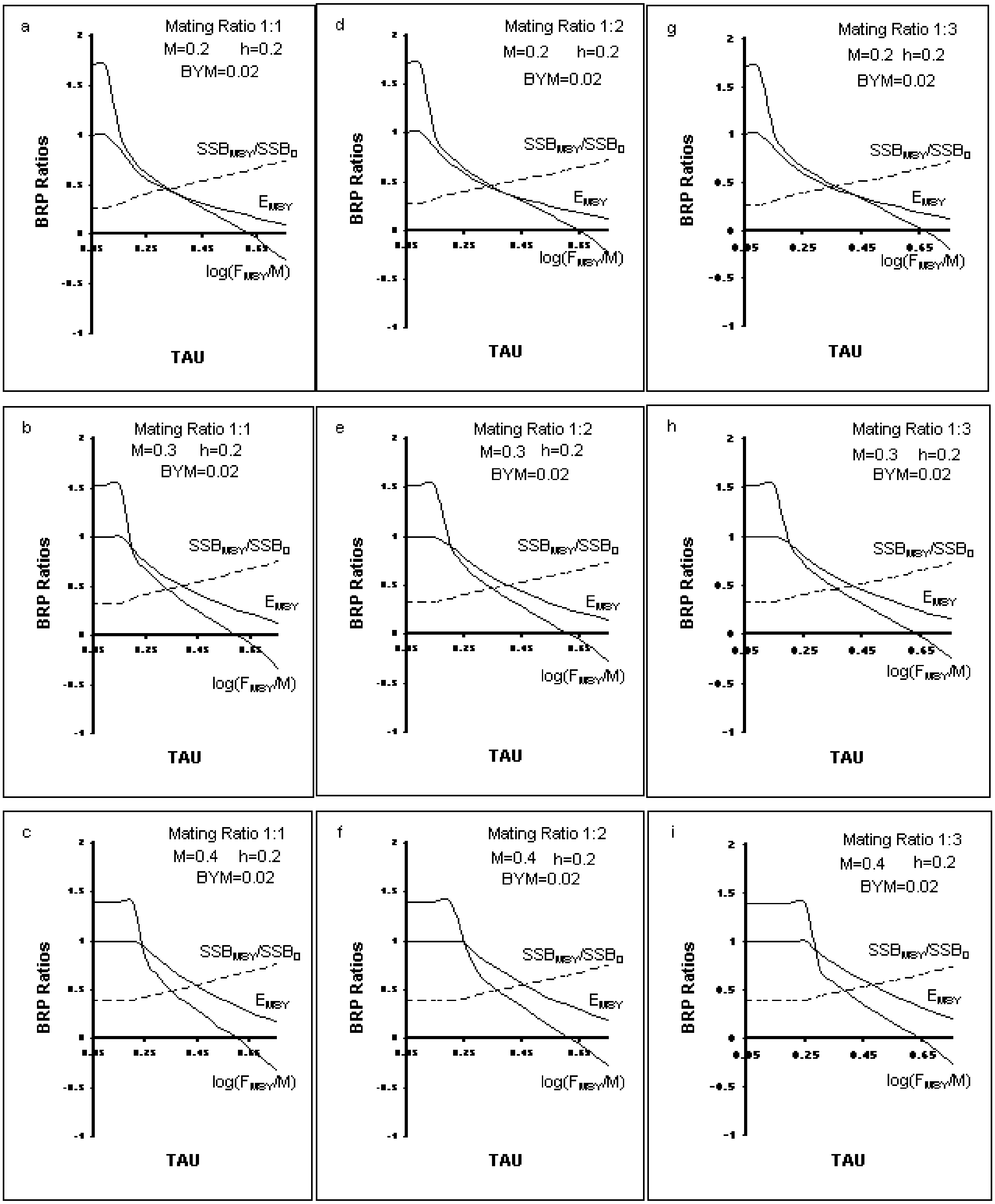

Figure 11. BRP ratios vs. Tau (τ) plots for Pribilof Islands blue king crab under Ricker (1954) stock-recruitment (*S-R*) relationship. τ = extinction parameter defining the shape of the *S-R* curve.

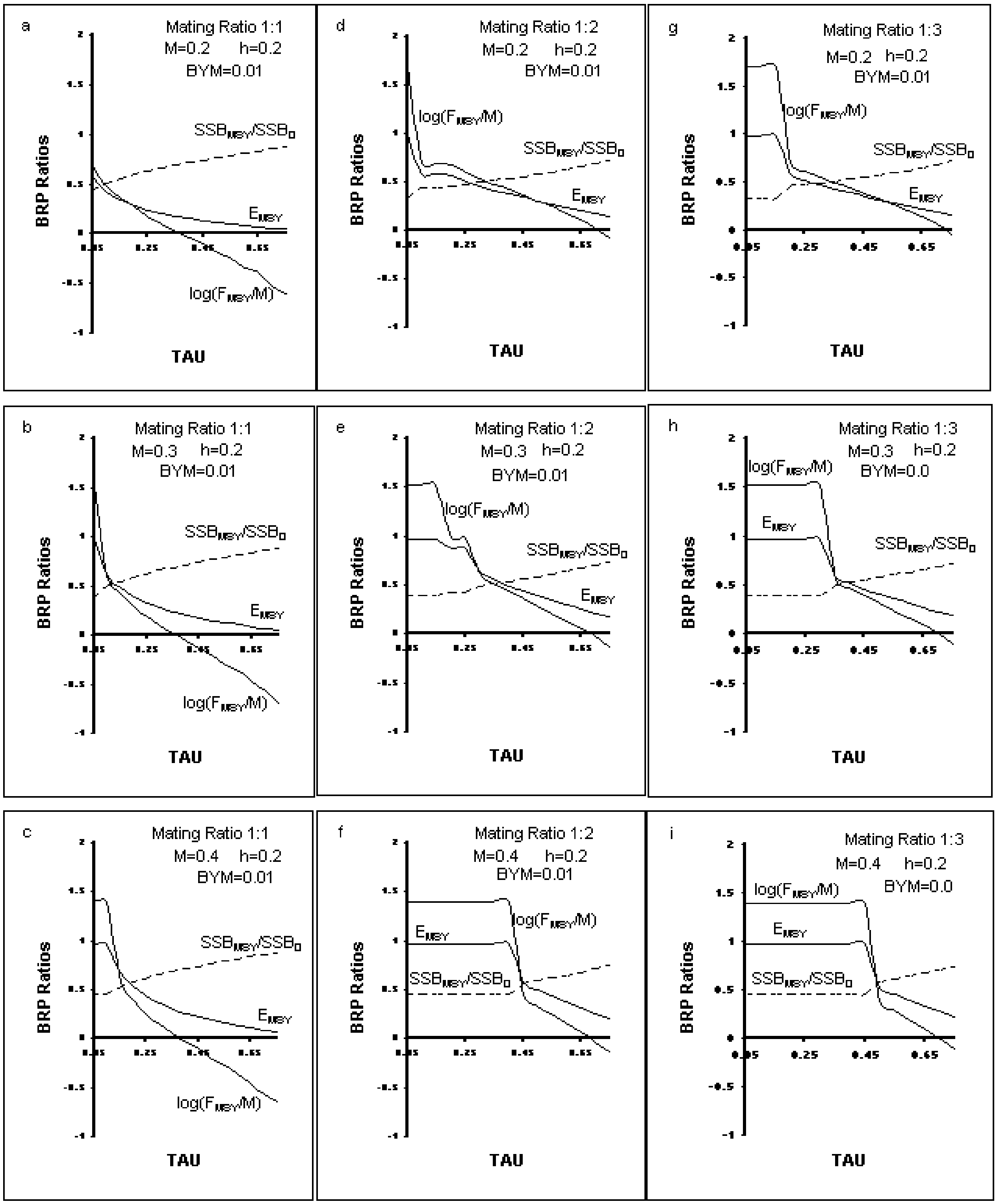

Figure 12. BRP ratios vs. Tau (τ) plots for Western Aleutian Islands golden king crab under Beverton and Holt (1957) stock-recruitment (*S*-*R*) relationship. τ = extinction parameter defining the shape of the *S*-*R* curve.

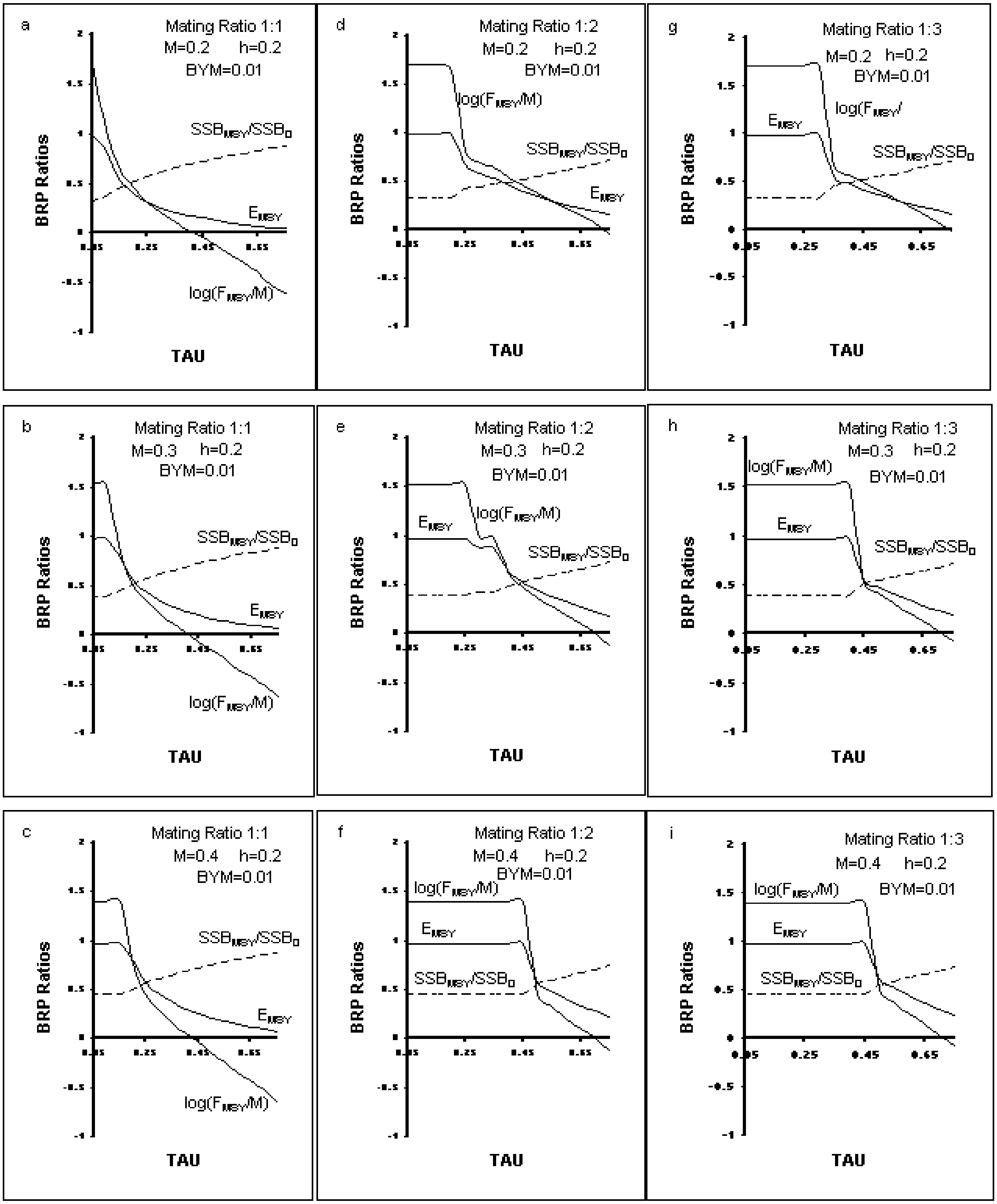

Figure 13. BRP ratios vs. Tau (τ) plots for Western Aleutian Islands golden king crab under Ricker (1954) stock-recruitment (*S*-*R*) relationship. τ = extinction parameter defining the shape of the *S*-*R* curve.

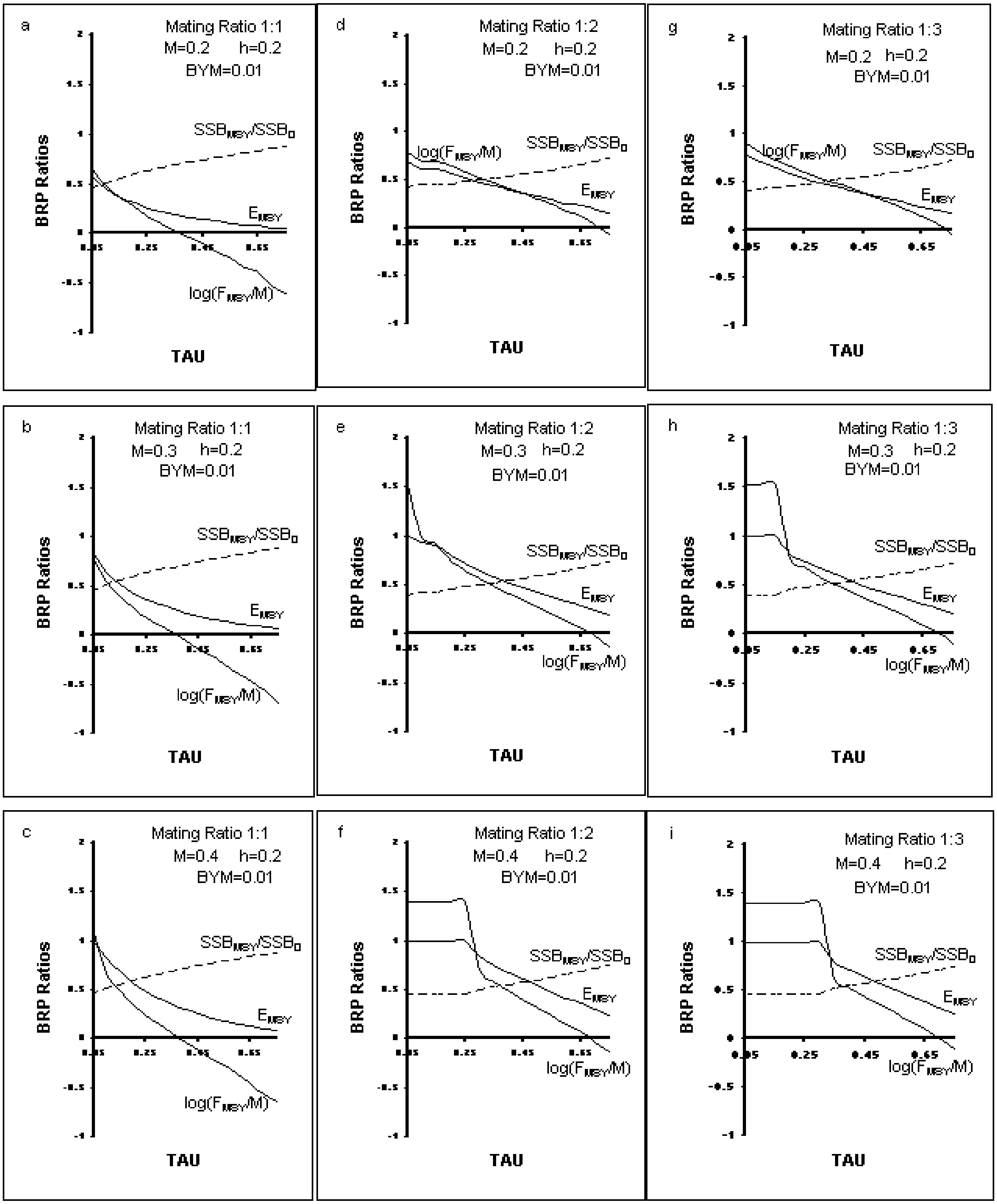

Figure 14. BRP ratios vs. Tau (τ) for Eastern Aleutian Islands golden king crab under Beverton and Holt stock-recruitment (*S*-*R*) relationship. τ = extinction parameter defining the shape of the *S*-*R* curve.

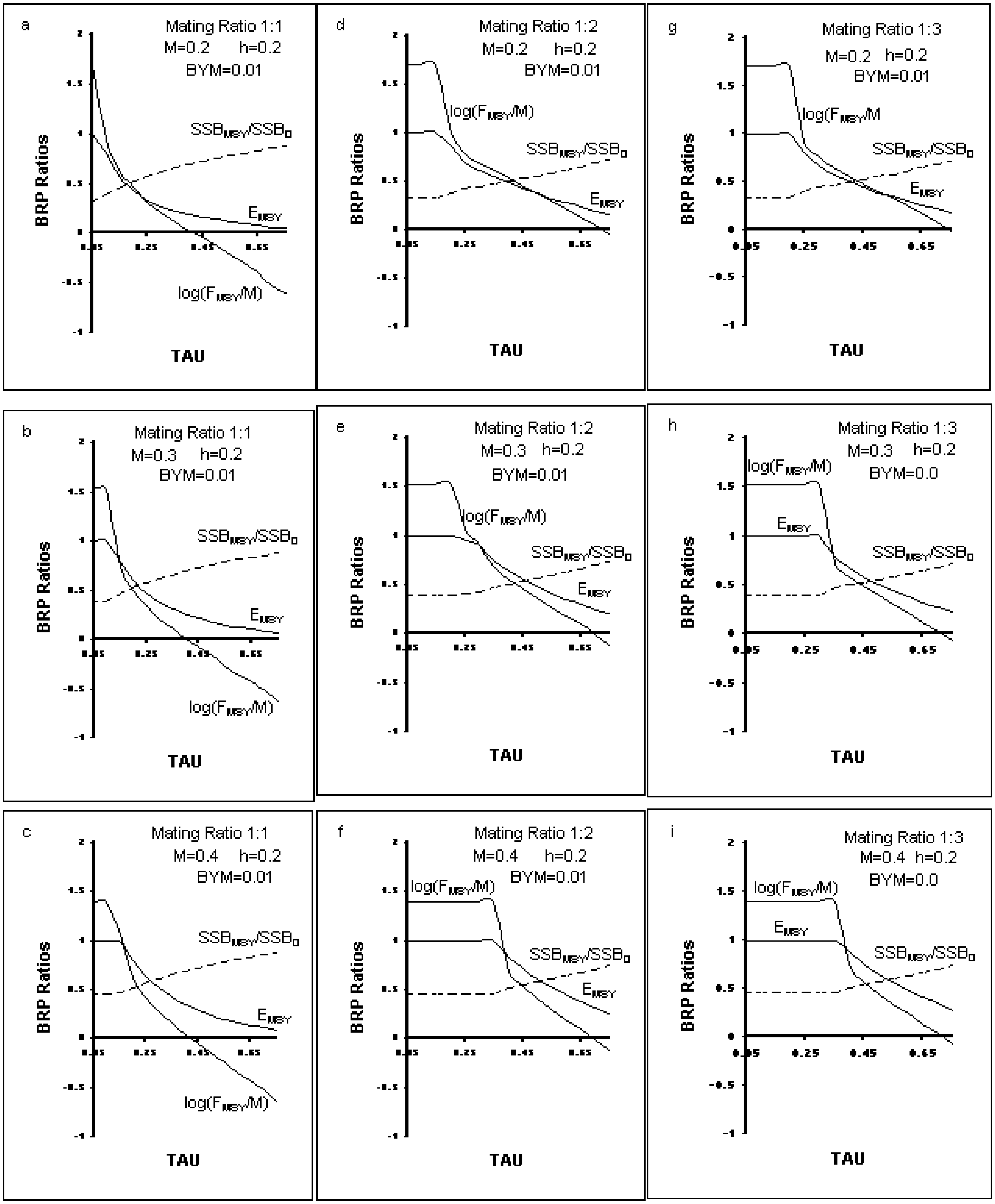

Figure 15. BRP ratios vs. Tau (τ) for Eastern Aleutian Islands golden king crab under Ricker (Ricker 1954) stock-recruitment (*S*-*R*) relationship. τ = extinction parameter defining the shape of the *S*-*R* curve.